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A Framework to Assess Alternative Vertical Line Rope Technology to Alleviate North Atlantic Right Whale Entanglement

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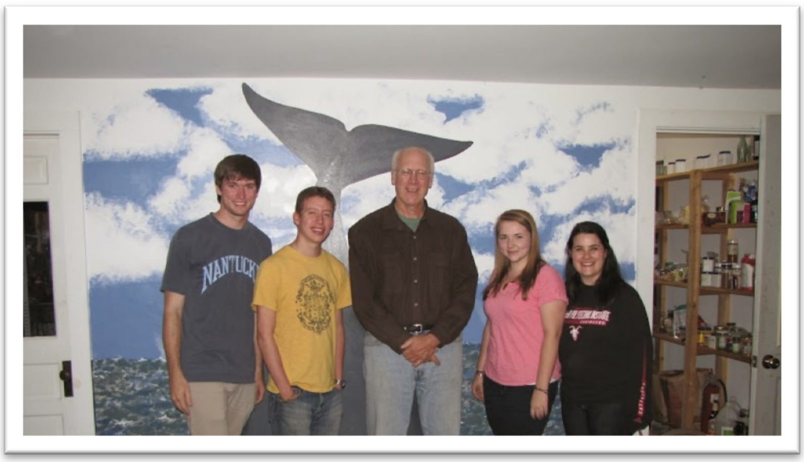

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Abstract

The North Atlantic right whale (NARW) is an endangered species whose population is negatively impacted by entanglements in fishing gear. The goal of this project was to determine the characteristics of a rope for use in the vertical lines of lobster traps that would be safer for NARWs and effective for lobster fishing. To complete our goal, we conducted interviews with whale researchers and analyzed entanglement case studies. We then created a multivariable assessment tool to assess potential alternatives to current ropes used for lobster fishing. We then assessed seven alternatives to current ropes to display the tool's effectiveness. The New England Aquarium sponsored this project and we recommend that they continue to use our multivariable assessment tool as well as conduct further research on rope alternatives.

Executive Summary

Background

The North Atlantic right whale (NARW) population was depleted during the Whaling Era and it has not been able to rebound since. Before the Whaling Era began in the first millennium, the North Atlantic right whale species thrived with a population estimate of 100,000 whales (Reeves et al., 2007, p. 41). Since the Whaling Era, the population of North Atlantic right whales has been able to recover slightly from an estimated lowest point of 85 individuals. At the time this report was written, their current population was 444 individuals (Waring et al., 2012, p. 1). However, there are still many threats hampering their ability to make a full recovery such as ship strikes and entanglements in fishing gear (Waring et al., 2012, p. 1). Prior to 2008, collisions with ships caused the highest number of identifiable non-natural deaths of North Atlantic right whales (Knowlton and Brown, 2007, p. 410). In 2008, a mandatory regulation was enacted forcing vessels over 65 feet in length to decrease their speeds in critical habitat areas of North Atlantic right whales. Since the implementation of this rule, the risk of North Atlantic right whales deaths due to vessel collisions has decreased by 80-90% (Conn and Silber, 2013, p. 10). However, entanglements in fishing gear are still a major threat to the North Atlantic right whales. At least 82% of the North Atlantic right whale population has scars consistent with fishing gear entanglements (Knowlton et al., 2012, p. 3). Of identifiable entangling gear, 55% can be attributed to lobster traps (Johnson et al., 2005, p. 640). Based on entanglement case studies, researchers hypothesized that most whales could break free from a 1,500 pound breaking strength rope compared to an average 3,500 pound breaking strength rope that is currently used (Knowlton et al., 2012, p. 26; McCarron and Tetreault, 2012, p. 4).

The goal of this project was to develop and test a framework with which to assess the characteristics of an alternative 1,500 pound breaking strength rope that would be safer for North Atlantic right whales and effective for lobster fishing.

Methodology

In order to accomplish our goal, we completed the following objectives:

1. **We identified the criteria a rope should meet in order to reduce the severity and duration of entanglements of North Atlantic right whales.** We explored the benefits and disadvantages to the whales resulting from different characteristics of rope. We compiled this information from two sources: interviews with researchers and analysis of right whale entanglement case studies. We used the information gathered from these two sources to create a list of considerations we used in the multivariable assessment tool.

2. **We determined the concerns that lobstermen have about introducing a rope alternative into the commercial lobster fishing industry.** We identified characteristics of current rope and their relative importance in the commercial lobster fishing industry. These features included, but were not limited to, compatibility with current equipment, durability, likelihood to

contribute to lost gear, and cost. We accomplished this by conducting interviews with ten lobstermen in Maine. We were able to supplement lobstermen responses by performing a stress-strain test on used rope we collected from a lobsterman. We used the information gathered from these sources to create a list of considerations we used in the multivariable assessment tool.

3. Investigated potential innovations in materials, manufacturing and existing ropes that could be applied to vertical lines of lobster traps. We investigated innovations in three areas to potentially decrease the duration and severity of entanglements. We found materials and manufacturing techniques that could produce rope alternatives with 1,500 pound breaking strength. In addition, we found existing ropes with 1,500 pound breaking strengths that were not marketed to the lobster fishing industry. We discovered at least two alternatives from each of these three categories. To establish a systematic process for collecting data about each potential alternative, we constructed a table for each alternative with the information we obtained. After compiling data on materials, manufacturing techniques, and existing ropes into a table, we assessed the alternatives with the multivariable assessment tool.

4. We developed and tested a multivariable assessment tool to assess potential rope alternatives based on findings from objectives one through three*.* We developed a framework to assess potential rope alternatives that takes into account the multiple perspectives relevant to this study. To accomplish this, we used Multi-Attribute Utility Theory (MAUT). MAUT is a multiple-criteria decision-making tool that is useful in risk analysis when a high level of uncertainty is involved (Tzeng and Huang, 2011, p. 194). In this project, we investigated alternatives to the current ropes used in the lobster fishing industry. In order to determine the feasibility of these alternatives, we assessed them on multiple perspectives. In developing the multivariable assessment tool, we considered the entanglement issue from multiple perspectives including: technical feasibility of introducing alternatives for vertical lines of lobster traps, safety of the whales and our ethical and legal responsibilities to them, and practical and economic concerns of the lobstermen. We identified the perspectives of both lobstermen and whale researchers as considerations that alternatives should be assessed on. We assigned these considerations a weight, which indicated their overall importance to the North Atlantic right whale entanglement problem. We assigned scores to alternatives based on how well they met these given considerations. We multiplied the scores by the weight of that consideration and then we summed the products for each alternative. The results from this multivariable assessment tool assisted us in formulating our conclusions and recommendations.

Findings and Discussion

From interviews with lobstermen and North Atlantic right whale researchers, analysis of entanglement case studies, and rope breaking strength data, we established the following findings:

1. Breaking strength of vertical line rope is an important factor when considering the safety of North Atlantic right whales. Through interviews with researchers and analysis of lobster gear involved in North Atlantic right whale entanglement case studies, we identified breaking strength as an important feature of rope when trying to protect North Atlantic right whales. Analysis of entanglement case studies involving vertical line of lobster traps demonstrated that the median breaking strength of rope involved in North Atlantic right whale entanglements from the case studies is greater than our goal of a 1,500 pound breaking strength rope. Therefore, 1,500 pounds may be a reasonable breaking strength to reduce the severity and duration of North Atlantic right whale entanglement and is consistent with whale researchers' current hypothesis.

2. The diameter of the vertical line rope is inversely proportional to the extent of North Atlantic right whale injury. Entanglements occur regardless of the diameter of the rope involved in entanglement but diameter may mitigate entanglement severity. In a study performed by Jeremy Winn regarding ropes' effects on right whale flippers and flukes, he concluded ropes with a smaller diameter cut significantly deeper into whale skin than larger diameter ropes (Winn et al., 2008, p. 340). On the basis of this study, it is widely accepted that a smaller diameter rope would increase the injury to whale, while a larger diameter rope would decrease the extent of whale injury.

3. Diameter of the vertical line rope is directly proportional to the breaking strength. As the diameter of a rope increases, the breaking strength also increases. Since a smaller diameter is more harmful to whales, breaking strength cannot be lowered by decreasing the diameter. If current manufacturing techniques could be altered so a larger diameter did not result in a rope with an increased breaking strength, there would be potential to create a safer rope for North Atlantic right whales that has a large diameter but a lower breaking strength.

4. Durability is one of the most important factors considered when lobstermen choose rope to use for the vertical lines of lobster traps. Ten lobstermen we interviewed from various areas in Maine noted durability as an important factor when selecting a vertical line. We determined four factors that affect the durability of vertical lines: UV light, interaction with the marine environment, forces exerted by the hauler, and fishing location.

5. Lobstermen who fish in muddy bottom areas reacted more positively to the idea of a 1,500 pound breaking strength rope than those who fish in rocky bottom areas. Lobstermen who fish in muddy bottoms did not believe that a reduction in breaking strength of their vertical line to 1,500 pound breaking strength would be a problem. In comparison, rocky bottoms impose much harsher fishing conditions than muddy bottom areas. The general consensus amongst lobstermen who fish in rocky bottom areas was a lower breaking strength rope would not work, as the rope could snap and they could lose more gear or cause serious injury to themselves.

6. 1,500 pounds is greater than the breaking strength of rope a lobsterman considered too weak for fishing. In one interview, a lobsterman gave us a rope that he deemed too weak to continue fishing with because he feared the rope would break and he would lose the gear. Of the three tests conducted, the average breaking strength of the rope was 1,279 pounds. This result indicates the potential of fishing with a 1,500 pound breaking strength rope in rocky bottom areas.

7. Lobstermen have concerns about their ropes' operational and safety specifications. From our interviews with lobstermen, we discovered that lobstermen use a variety of diameters ranging from 11/32 inches to 5/8 inches resulting from their different hauler configurations. The diameter of the vertical line affects safety and operational aspects of a lobstermen's job including compatibility with their equipment, tidal effects on the vertical line and buoy, ability to splice the rope, ability to handle when wet, flexibility, abrasiveness, and the specific gravity.

8. Rope replacement costs are high for lobstermen; therefore, cost is of great concern to them. Lobstermen have high yearly vertical line rope replacement costs, as revealed in our interviews. If something causes the vertical line to snap or break, gear may be lost, increasing lobstermen's replacement costs. Lobstermen we interviewed spent from $12,000 to $15,000 on new vertical line rope per year. Gear loss can cost the average lobstermen anywhere from $3,000 to $12,000 per year.

9. Shape memory materials have the potential to be an alternative material for lobster fishing ropes. Shape memory materials have the ability to be programmed to a customizable shape. Once programmed, the material can be placed into any position but when the material is returned to specific conditions, the material will revert back to its programmed orientation. We discovered two types of shape memory materials: shape memory alloys and shape memory polymers. Both of these materials could be programmed to coil once retrieved from the ocean yet remain straight while underwater. They could be incorporated into the fibers of lower breaking strength ropes.

10. The addition of a coating to a vertical line rope with a breaking strength of 1,500 pounds could make the vertical rope line more appealing to lobstermen and less harmful to North Atlantic right whales. Coatings are synthetic liquids that are applied to a finished rope to create a barrier around the rope. The purpose of applying a coating is to enhance characteristics of the rope, such as durability and abrasion resistance. From reviewing manufacturers' websites and online inquiries, we determined three coating options that could be viable additions to lower breaking strength rope: Maxijacket urethane coating, TrueKote CS-100, and TrueCoat CS-252.

11. There are existing ropes that could serve as alternative lower breaking strength rope in the lobster fishing industry. We found two ropes, Duraflex Lead Core rope and Norpacific Gillnet Corkline High Tenacity rope, which both have inner cores surrounded by protective sleeves. The sleeves allow for high abrasion resistance and UV resistance, which makes the rope both easy to handle and durable.

12. Our multivariable assessment tool is an effective framework when assessing rope alternatives because it incorporates all of the perspectives relevant to lessening the extent and severity of North Atlantic right whale entanglement. Through our assessment of alternatives, we discovered that our multivariable assessment tool is useful in the evaluation process. The tool compiles specific considerations of alternatives that must be included in the assessment as well as the relative importance of those considerations. In addition, we assigned an uncertainty rating for each alternative based on how many considerations it could be assessed on. The tool allows for a multi-dimensional assessment of any alternative. The multivariable assessment tool also assists the users in identifying gaps in knowledge that should be further pursued.

Recommendations

Based on our literature review and empirical research, we established the following recommendations for the New England Aquarium and researchers working to help alleviate the problem of North Atlantic right whale entanglements:

Future Plans to Assess Alternative Ropes

1. **We recommend future proposed rope alternatives be assessed using our multivariable assessment tool through cooperation between all relevant perspectives.** Our multivariable assessment tool provides a valuable framework that encompasses a variety of perspectives that are relevant to the problem presented by entanglement of North Atlantic right whales. Incorporation of the various perspectives is essential so all parties feel as though their perspectives are considered in potential solutions. A multivariable assessment tool, exemplified by the one we have produced, could be effective in determining the most optimal solution.

2. **We recommend different vertical line rope alternatives be pursued in fishing areas with different conditions.** An overwhelming consensus amongst lobstermen we spoke with and researchers we interviewed was that different fishing locations have drastically different needs, especially when differentiating between inshore and offshore fishing or muddy and rocky bottom areas. A single vertical line rope alternative may not be successful across the entire lobster fishing industry. Therefore, researchers and lobstermen alike should identify criteria alternatives rope must meet in different regions.

3. **We recommend not pursuing a specific alternative until it has been thoroughly researched.** A low total score on the multivariable assessment tool does not indicate a less optimal solution. In our assessment, low total scores revealed a lack of information, rather than poor potential performance. Alternatives with high total scores and low uncertainty scores may be the most promising solutions to pursue. Therefore, we recommend only alternatives with low uncertainty ratings and high scores be subjected to further in-field testing or implementation to increase the likelihood that changes will be successful.

4. **We recommend the next step in researching shape memory materials is determining whether the technology can be manufactured into a viable rope.** Shape memory materials have potential as lobster fishing rope alternatives. To test the characteristics of a shape

memory material alternative, the technology first needs to be manufactured into a workable rope. If a rope could be produced, the New England Aquarium research team or the Bycatch Consortium could distribute the rope along the coast of Maine and Massachusetts to lobstermen. To further assess the effectiveness, the lobstermen could then score the shape memory materials with our multivariable assessment tool.

5. **We recommend experimental testing with rope coatings.** Applying a synthetic coating to a vertical line of a lobster trap with a breaking strength of 1,500 pounds could make the rope line more appealing to lobstermen and less harmful to North Atlantic right whales. We recommend lower breaking strength ropes be coated with the three coatings discussed in Finding 10 and given to lobstermen in Maine and Massachusetts to test under fishing conditions. The lobstermen would then be able to reassess the rope on our multivariable assessment tool and provide a more informed total score. If the new score reflects an increase in feasibility compared to current rope and still satisfies the considerations that provide a safer alternative for North Atlantic right whales, large scale implementation could then be possible.

6. **We recommend giving samples of the existing ropes we explored to lobstermen to determine the feasibility of implementing them in the vertical lines of lobster traps.** There are existing ropes that could serve as alternatives for lower breaking strength rope in the lobster fishing industry. However, there are insufficient data regarding the feasibility of these existing ropes in the lobster fishing industry. Even though these ropes are currently used in marine environments, they have not been tested under the rigorous conditions lobstermen put their gear through. The best way to determine how these ropes will perform is to purchase samples to distribute amongst lobstermen along the coast of Maine and Massachusetts.

7. **We recommend researchers use the right whale entanglement simulator to further determine how the breaking strength of vertical lines of lobster traps affects the safety of North Atlantic right whales.** The breaking strength of vertical line rope is an important factor when considering the safety of North Atlantic right whales. More research is necessary to explore the implications of a 1,500 pound breaking strength rope on North Atlantic right whales. We recommend that the right whale entanglement simulator be used. The project, which is currently under development, would allow a computer simulation to test the interactions between vertical line rope and North Atlantic right whales. If the rope can be designed to have a 1,500 pound breaking strength, evidence of the ideal breaking strength could be determined in a non-harmful way to the whales.

8. **We recommend conducting further research to determine the relationship between rope diameter and extent of whale injury resulting from entanglement.** The diameter of the vertical line rope is inversely proportional to the extent of North Atlantic right whale injury. After reviewing Woodward and Winn's right whale tissue studies, we determined that ropes with a thicker diameter should be tested against tissue samples. In the studies, the largest diameter used was 3/8 inch; however, after interviewing lobstermen, many actually use ropes larger than

3/8 inch which is discussed in Finding 7 (Winn et al., 2008, p. 330). The evidence could potentially provide a range of diameters that would be significantly less harmful to North Atlantic right whales.

Proposed Future WPI Projects

9. We recommend a project dedicated to the implementation of a new gear marking system. From our interviews with right whale researchers, we concluded determining the origin of gear retrieved off of North Atlantic right whales is extremely difficult. Currently, there is a system that registers and marks buoys so that lobstermen recognize which gear is theirs. However, when gear is retrieved off of North Atlantic right whales, the buoys or traps are not necessarily attached and gear cannot be identified. As a result of a poor gear marking system, the entanglement data available for research is limited. Therefore, we strongly recommend that future research investigates how to implement a gear marking system that would allow researchers to collect more information regarding gear involved in entanglements. If researchers can confirm that North Atlantic right whale entanglements occur in specific areas, future modifications could be implemented in only those areas as opposed to the entire industry.

10. We recommend a project dedicated to raising lobstermen awareness of North Atlantic right whales. Through our interviews with lobstermen, we concluded that some lobstermen do not understand the overlap of North Atlantic right whales and their gear. An educational program could help educate lobstermen about North Atlantic right whales and their interaction with the lobster fishing industry. An educational program could consist of a combination of brochures, YouTube videos, social media campaigns, and presentations.

Conclusions

This project developed a framework with which to assess the potential for 1,500 pound breaking strength alternative ropes for use in the lobster fishing industry that would be safer for North Atlantic right whales. With 82% of the North Atlantic right whale population affected by entanglements, a reduction of entanglements is critical. Alternative ropes would be used in the vertical line rope of lobster traps, which are the main identifiable source of North Atlantic right whale entanglements. As part of our project, we developed a multivariable assessment tool with the purpose of providing a method to assess rope alternatives. Our multivariable assessment tool does more than simply assess the alternatives we determined; it provides a framework to involve all stakeholders in this incredibly complex problem. Cooperation between researchers, manufacturers, and lobstermen is essential to save the remaining individuals in the North Atlantic right whale population. This tool provides a method for collaborative and constructive cooperation.

We then applied and tested this tool. We determined the considerations necessary to increase the safety of North Atlantic right whales through analysis of entanglement case studies and interviews with whale researchers. To incorporate the perspectives of lobstermen, we performed interviews with ten Maine lobstermen and supported those interviews with a stress strain test on a sample of used rope. We investigated innovative materials, coatings, and existing ropes that could be given to the New England Aquarium to develop further. We also provided the New England Aquarium with a detailed analysis of all alternatives assessed on this tool. In addition to data sheets about the alternatives we assessed, we provided our multivariable assessment tool and protocol for using it. Our findings and multivariable assessment tool could be useful long past the scope of this project. We hope that our multivariable assessment tool will aid researchers in developing gear modifications that have a lasting, positive impact on the North Atlantic right whale species as a whole.

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1.0 Introduction

The North Atlantic right whale population was decimated during the Whaling Era and it has been unable to rebound to sustainable levels. Before the Whaling Era began in the first millennium, the North Atlantic right whale species thrived, with a population estimated at 100,000 whales (Reeves et al., 2007, p. 41). Tragically, by the end of the Whaling Era in 1935, this benign, colossal creature was so rare it was thought to be extinct (Kraus and Rolland, 2007, p. 5). However, right whales were spotted in Cape Cod Bay, the Gulf of Maine, and the Bay of Fundy in the 1960's and have a population currently estimated to be 444 individuals (Kraus and Rolland, 2007, p. 6; Waring et al., 2012, p. 1).

Human actions decreased the population of North Atlantic right whales and therefore we have an ethical responsibility to help this species recover. Since the species is endangered, the death of a single whale has a greater impact than if the population was abundant. A death does not only affect that individual, it affects the species as a whole. Therefore, we have an ethical responsibility to ensure their safety and well-being. Over the years, humans took legal action such as the International Whaling Commission Moratorium on Commercial Whaling, the Marine Mammal Protection Act, and the Endangered Species Act to ensure the protection of North Atlantic right whales (Reeves et al., 2007, p. 41). While the Southern right whale population has been able to recuperate, obstacles have slowed the recovery of the North Atlantic right whale population (NOAA Fisheries, 2012).

Most of these obstacles are based on whale-human interaction; in particular, ship strikes and fishing gear entanglements (Knowlton and Kraus, 2001, p. 4). Approximately half of all deaths of North Atlantic right whales can be attributed to vessel collisions and entanglements in fishing gear (Moore et al., 2007, p. 376). In recent years, the National Oceanographic and Atmospheric Administration issued mandatory regulations that changed the maximum speed vessels could travel in established habitat areas of the North Atlantic right whale (NOAA, 2008, p. 1). Since these regulations were enacted in 2008, there has been a dramatic decrease in the risk of vessel collisions (Conn and Silber, 2013, p. 1). However, the problem of entanglement in fishing gear still poses a serious threat. For example, scientists report that 82% of North Atlantic right whales documented have scars from entanglement (Knowlton et al., 2012, p. 3).

Entanglements in fishing gear can result in severe injury or death. Nets or ropes can wrap around a whale's body and mouth and cause pain, foraging difficulties, and lack of circulation in extremities (Kraus and Rolland, 2007, p. 20). When a source of gear can be determined, 49% of North Atlantic right whale entanglements are attributed to lobster trap gear (Johnson et al., 2005, p. 640). As a means to reduce entanglement, researchers modified gear because gear modifications have been successful in protecting other species (Griffin et al., 2008, p. 3). For example, before gear modification occurred, roughly 770 sea turtles were killed every year by trawl nets along the Atlantic coast. Then, in 2003, National Marine Fisheries Service mandated that a Turtle Excluder Device be used in every trawl net. Studies have shown that since this rule was implemented, turtle mortalities from fishing nets have decreased by 97% (Griffin et al., 2008, p. 3). Since gear modification has been proven effective, research has been focused on modifying the rope used for vertical lines of lobster traps.

Gear modification strategies can be divided into three categories: modifications that remove ropes from the water column, modifications that take advantage of the sensory capabilities of whales, and modifications that alter the physical characteristics of the rope itself (S. Kraus, personal communication, September 18, 2013). Rope-less fishing has been explored; but due to the cost, it may not be easily implemented into the industry at this time (The Large Whale Entanglement Working Group, 2008, p. 5). Sensory research exploring the correlation between rope color and whale detection behavior is currently being conducted but there is no evidence indicating a whale would avoid a rope based on its color (S. Kraus, personal communication, September 18, 2013). In terms of modifying the physical characteristics of ropes, one of the most promising modifications is the development of a rope with a lower breaking strength than what is currently used in the industry. Specifically, researchers hypothesize that most whales could break free from a 1,500 pound breaking strength rope (Knowlton et al., 2012, p. 26). While a 1,500 pound breaking strength rope has been made and tested, it has not been proven to be both safer for whales and effective for lobster fishing (T. Werner, personal communication, April 11, 2013).

The goal of this project was to develop and test a framework which to assess the characteristics of an alternative 1,500 pound breaking strength rope that would be safer for North Atlantic right whales and effective for lobster fishing. To achieve this goal, we interviewed whale researchers and analyzed entanglement case studies to understand how to make ropes safer for North Atlantic right whales; interviewed lobstermen to better understand the characteristics of rope important for lobster fishing; investigated innovations in material science, manufacturing, and existing ropes that could be applied to the vertical lines of lobster traps; and compiled all of this collected information to develop and test our multivariable assessment tool.

Based on our findings, regarding whale safety, lobstermen concerns, and possible rope alternatives, our recommendations identified gaps in knowledge on our multivariable assessment tool and how further research could fill these gaps. We then provided recommendations for how to pursue the identification and testing of future vertical line rope alternatives. We proposed recommendations to the New England Aquarium regarding the next steps in the development of proposed, alternative 1,500 pound breaking strength ropes.

2.0 Background

In this chapter, we begin with a discussion of the natural history of North Atlantic right whales as well as past and present threats the population has faced or is facing. We then review previous efforts to encourage a rebound in the population. We present a review of prior efforts to alter fishing gear, including preliminary testing on lower breaking strength rope. We conclude by discussing the Consortium for Wildlife Bycatch Reduction at the New England Aquarium and their needs for a lower breaking strength rope that could be effective in lobster fishing.

2.1 Natural History of North Atlantic Right Whales

The North Atlantic right whale (*Eubalaena glacialis*) is one of the rarest large whale species, known for their distinctive appearance, which can be seen in Figure 1. They spend the spring, summer, and fall months in feeding areas including Massachusetts and Cape Cod Bays, the Bay of Fundy, as well as the Scotian Shelf. They migrate to these waters from their calving grounds in coastal Florida and Georgia where they spend the winter months (NOAA Fisheries, 2013b). The prey of the North Atlantic right whale is zooplankton, including copepods, euphausiids, and cyprids. To extract zooplankton from the water, the North Atlantic right whales swim with their mouths open and use baleen to strain their prey from the water (NOAA Fisheries, 2013b). Right whales can feed at the surface and are therefore classified as skimmers.

Figure 1: North Atlantic right whales (Georgia Department of Natural Resources, Permit 15488)

The whales are black with white callosities, or rough skin patches, located on the head, and do not have a dorsal fin. Their white callosities are similar to human fingerprints in that they allow for differentiation between each whale (Kraus and Rolland, 2007, p. 13). The whales can also be distinguished by their V-shaped blow and all-black tail. Weighing up to 70 tons, these whales grow to be about 50 feet long, with calves born at 14 feet in length (NOAA Fisheries, 2013b). However, one of the most distinctive features of the North Atlantic right whale is its small population size as a result of the Whaling Era.

2.2 Whaling Era

Whaling began in the first millennium in the Atlantic Ocean. The hunting of whales is described as "*...one of the most extensive, prolonged, and thorough campaigns of wildlife exploitation in all of human history*" (Reeves et al., 2007, p. 41). Whales were hunted primarily for their blubber which was converted to whale oil and used as an energy source. The North Atlantic right whale was one of the most hunted whale species due to its high blubber content, high quality oils, low speed, and its buoyancy after death (Kraus and Rolland, 2007, p. 4). Therefore, they were the "right whale" to hunt during the Whaling Era. The estimated population of North Atlantic right whales was believed to be slightly less than 100,000 individuals prior to the start of whaling (Reeves et al., 2007, p. 41). At its lowest level, the population may have dropped to a *mere 85 individuals* (Kraus and Rolland, 2007, p. 5). Due to the large number of whales killed, a moratorium on whaling was enacted in 1935 which put an end to the Whaling Era (Kraus and Rolland, 2007, p. 60).

2.2.1 Effects of the Whaling Era on North Atlantic Right Whales

Although the Whaling Era ended over 85 years ago, it continues to affect the North Atlantic right whales. It is believed "... that this extensive history of harvesting has resulted in the current small population size, low genetic variation, and decreased reproductive capacity in the species" (Frasier et al., 2007, p. 205).

Today, *the most recent estimate of living North Atlantic right whales is 444 individuals*, which is based off data from 2009 (Waring et al., 2012, p. 1). However, the actual population size may be slightly larger due to the high probability of unobserved whales. The population of North Atlantic right whales is estimated based on data in the *North Atlantic Right Whale Catalog*. The *Catalog* is composed of all North Atlantic right whale sightings since the late 1980s. Presumed living whales, which are determined by those that have been seen in the last six years, are included in the population estimate (Hamilton et al., 2007, p. 91).

Lack of genetic variability and low reproductive rates are intrinsic factors preventing the North Atlantic right whales from recovering. A lack of genetic variation contributes to the low reproductive rate of female North Atlantic right whales. Since the genomes of breeding individuals are so similar, the lack of genetic variety decreases the number of viable offspring. Only five haplotypes, or mitochondrial control region sequences, remain in the current North Atlantic right whale population (Frasier et al., 2007, p. 211). Aborted pregnancies and neonatal mortalities are hindering the population's ability to recover since a female has her first calf at around five years old (Knowlton et. al, 1994, p. 1302). However, there are reproductive aged females that have never been known to bear a calf (Kraus et al., 2007, p. 190). Given these considerations, *any external factors that hamper recovery are placing unnecessary stress on the species*.

2.3 Preservation of North Atlantic Right Whales

When considering the plight of the North Atlantic right whale, the ethical responsibility we as humans have to the animal must be considered. *Preservationism* is the belief that all species should be kept alive, regardless as to whether or not humans could benefit from their existence. The philosophy behind preservationism is that every animal has ethical value and *endangered species have a greater ethical value because of their rarity* (Bradley, 2001, p. 44). Holmes Rolston states "Every extinction is a kind of super killing, it kills forms (species), beyond individuals. It kills 'essences' beyond 'existences', the 'soul' as well as the 'body'. It kills collectively, not just distributively" (Rolston, 1998, p. 75). The effect of killing a species has a greater impact than killing an individual animal because an entire kind of being would be lost. According to preservationism, it is our ethical duty to the animal, to the species, and to ourselves to preserve them. Following this line of thinking, efforts should be taken to protect the North Atlantic right whale because there are so few of them. The deaths of a few whales greatly impact all members of the population. *Deaths of these whales have such an impact that population decline could potentially be reversed by the preservation of just two reproductive females each year* (Kraus and Rolland, 2007, p. 4).

2.3.1 Measures Taken to Ensure Preservation

The Marine Mammal Protection Act (MMPA) of October 21, 1972 protects all marine mammals and specifically prevents the taking of marine mammals. As a marine mammal, the North Atlantic right whale is protected under this Act. *Taking* is defined as the action of or an attempt to "harass, hunt, capture or kill any marine mammal" (NOAA Fisheries, 2013a). The Act bans the taking of marine mammals that are located in U.S. waters, blocks citizens from the taking of marine mammals in the high seas, and prevents marine mammals and their products from being imported into the United States. In 1994, the Act was amended to allow takings for the purpose of authorized research. The amendment also created a program that oversees taking due to commercial fishing and stock assessments for all marine mammals (NOAA Fisheries, 2013a).

While the MMPA was passed in the United States, no single country sufficiently protected North Atlantic right whales or other endangered species. Therefore in 1973, eighty nations signed the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). CITES stopped the international trade of animals if that trade was detrimental to a species. In order to install CITES protection in the United States, the United States passed the Endangered Species Act in 1973. The Endangered Species Act (ESA) also holds federal agencies responsible to conserve the endangered species and prevents any individual or organization from harming a species or its critical habitat (United States Fish and Wildlife Service, 2012a). The ESA defines *endangered* as a species that is at risk of extinction throughout all or most of its habitat, while *threatened* refers to a species with a high chance of becoming endangered in the near future (United States Fish and Wildlife Service, 2012b). The goal of the Endangered Species Act is to recover the listed species to a population number that would eliminate the species' need for protection (United States Fish and Wildlife Service, 2013, p. 1). The North Atlantic right whale was listed as endangered in 1970 (NOAA Fisheries, 2013b).

2.4 Contemporary Threats to Whales

The North Atlantic right whale remains endangered, in part, due to its frequent interactions with humans. The two most recent threats faced by North Atlantic right whales are ship strikes and entanglement in commercial fishing gear. Measures taken to reduce North Atlantic right whale mortality from ship strikes have been successful. However, while efforts to eliminate or reduce entanglement have been explored, no definitive solution has been found.

2.4.1 Ship Strikes

A significant number of vessels travel through regions highly populated by North Atlantic right whales, seen in Figure 2.

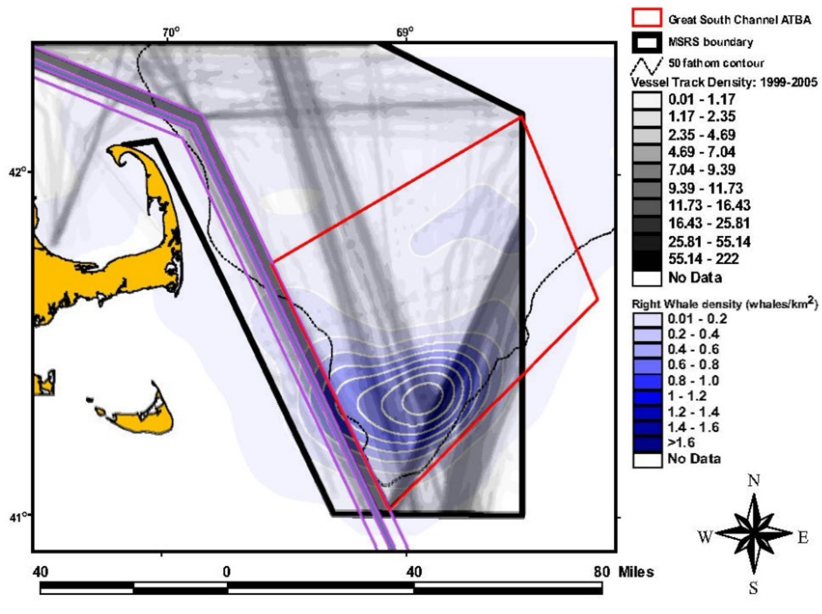

Figure 2: Map of the Great South Channel with the vessel track density in black and the right whale density in blue (NOAA Fisheries, 2007)

This overlap greatly increases the likelihood that ships will encounter whales, *making vessel strikes the deadliest threat to North Atlantic right whales* (Knowlton and Brown, 2007, p. 410). Ship strikes are defined as collisions between whales and vessels. Necropsies, or examinations of deceased whales, attribute *50% of documented North Atlantic right whale deaths prior to 2008 to ship strikes* (NOAA, 2008, p. 3). Whales are frequently hit by propellers located on the bottom of ships or experience blunt trauma from the bow of the boat. Vessels larger than 24 meters or those travelling at 26 km/h pose the greatest risk of mortality to North Atlantic right whales (Knowlton and Brown, 2007, p. 419). Therefore, altering speed limits in areas inhabited by right whales has been an important and successful mitigation strategy. Ships greater than 65 feet must travel at speeds of 10 knots or less during periods where whales occupy the same waters. *Since this rule went into effect in 2008, the risk of right whale mortality resulting from ship strikes has decreased by approximately 80-90%* (Conn and Silber, 2013, p. 10).

2.4.2 Entanglements

The second leading threat to North Atlantic right whales is entanglement in fishing gear. Entanglement is when nets or ropes wrap around an animal. Entanglements harm the whales by cutting into their skin leaving severe lacerations which can become infected (Figure 3).

Figure 3: Scarring from entanglement on the fluke of a right whale (The New England Aquarium)

Ropes can also decrease circulation in whales' extremities if the rope wraps around a fin or the flukes. If entanglement occurs in or around the rostrum, or mouth of the whale, the whale may struggle to feed and starve (Knowlton, 2012, p. 8). The number of right whales who show evidence of gear attachment has increased from 1980 to 2011. Considering that the North Atlantic right whale species is critically endangered, a death from the entanglement of one whale is a small, but significant percentage of the total population. Currently, *82% of documented North Atlantic right whales have scars consistent with entanglement in fishing gear* (Knowlton et al., 2012, p. 3). Gear is difficult to retrieve from entangled whales but when it is retrieved, *lobster gear is responsible for 55% of identifiable entanglements* (Johnson et al., 2005, p. 640).

2.5 Lobster Fishing and its Effects on North Atlantic Right Whales

In 2011, Maine, Massachusetts, and New Hampshire authorized a combined total of 1,198,239 lobster traps (M. Jacob, personal communication, May 8, 2013). Lobster traps are sent down to the ocean floor in a daisy chain technique in groups of three to fifteen traps. A typical lobster trap configuration up can be seen in Figure 4. Traps are connected together by sinking groundline rope (McCarron and Tetreault, 2012, p. 6). The gear is typically submerged anywhere between three days to multiple weeks depending on the time of year (McCarron and Tetreault, 2012, p. 7). When the traps are harvested, the daisy chain system between traps allows lobstermen to haul large numbers of traps one after another using their hydraulic hauler (Pol and Carr, 2000, p. 334).

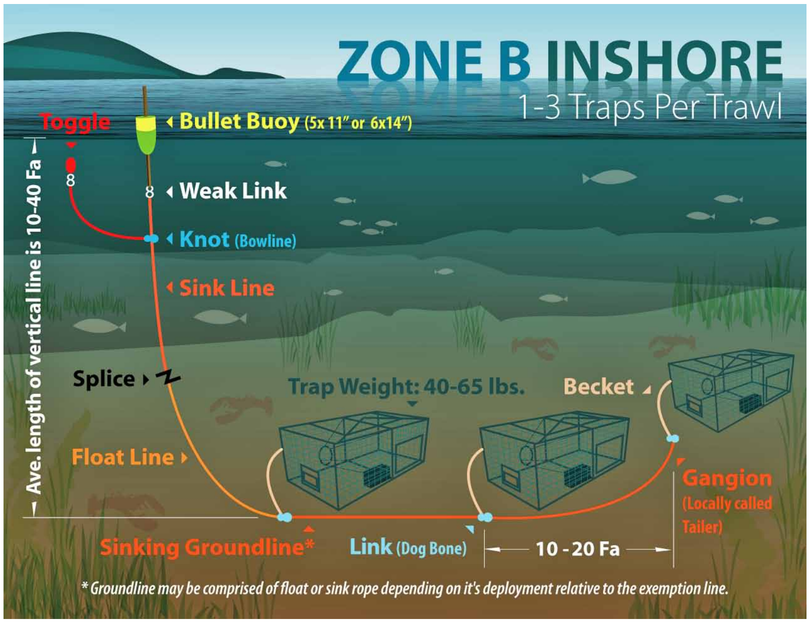

Figure 4: Diagram of typical Maine Zone B inshore lobster traps configuration (McCarron and Tetreault, 2012)

A standard hauler used by lobstermen consists of a hydraulic motor attached to two plates which can be seen in Figure 5. These plates form a V-shaped notch into which the rope is fed. When the plates are rotated, the rope is squeezed in the notch thus reeling in the rope (Preston, R. W., 1993, p. 6). This process increases the amount of wear on the rope. These ropes, called vertical lines, connect traps to a surface buoy.

Figure 5: Hauler removed from lobster fishing vessel (Tyler Ewing)

Typically for inshore fishing, there is one vertical line ranging from 60 to 210 feet for every one to three traps. For offshore fishing, there are typically two vertical lines ranging from 120 to 480 feet for every set of 3-15 traps, called trawls. There is a regulation in place mandating that the top 1/3 of the vertical must be sinking rope (McCarron and Tetreault, 2012, p. 30). The lengths of these vertical lines vary due to the depth of the water column plus additional rope added for slack (McCarron and Tetreault, 2012, p. 7). *Of whale entanglements attributed to lobster traps, 57% were directly related to the vertical lines* (Johnson et al., 2005, p. 641).

2.5.1 Ropes Used in Lobster Fishing

Prior to the 1950's, vertical lines used cotton or natural fiber ropes which had breaking strengths of 2,000 pounds (McKenna et al., 2004, p. 53). In the 1950's, the industry began using polymers to make stronger and more durable ropes (Knowlton, 2012, p. 3). Then, in 1992, copolymer technology, a technique in which polymers are combined in different ratios to achieve desired properties, was developed. Different polymers are now used in combination to create even stronger ropes (Knowlton, 2012, p. 3). Fishermen adopted polymer ropes because they are lighter than their cotton counterparts, have increased breaking strengths that reduce gear loss, and are more resistant to wear. Common ropes used today are made out of polyethylene and polypropylene with diameters ranging from 1/4 to 1/2 inch and breaking strengths ranging from 1,200 to 4,100 pounds (McCarron and Tetreault, 2012, p. 11; McKenna et al., 2004, p. 53). *The increased breaking strength of ropes correlates to the number of increased entanglements over the same time period* (Knowlton, 2012, p. 22). Therefore, reversing the trend of increased breaking strength could also reverse the trend of increased entanglements.

2.5.2 Correlation between Properties of Rope and Severity of Entanglements

When a right whale has become entangled in a vertical line, characteristics of the rope affect the severity of the entanglement. In order to determine the impact *diameter* and *abrasion* have on the right whale during an entanglement, Becky Woodward and Jeremy Winn conducted two separate studies. In these studies, a testing apparatus was created to accurately replicate the effects of rope on an entangled whale swimming. This test rig included specimens of deceased right whale flukes and flippers in order to accurately test the effects of the rope (Woodward et al., 2006, p. 301; Winn et al., 2008, p. 329). The different characteristics of the rope were quantified based on their cutting ability into the whale's epidermal layer. The results of the study indicated that diameter had a great effect on the whale's skin. When comparing a 1/4 inch rope to a 3/8 inch rope, *the 1/4 inch rope cut considerably deeper into the epidermis* (Winn et al., 2008, p. 334). The study also related the condition of the rope to the severity of ensuing lacerations. *Due to the higher abrasiveness of the older rope, it had a greater cutting ability into the whale's skin* (Woodward et al., 2006, p. 304).

In addition, the research team at the New England Aquarium, in conjunction with the Provincetown Center for Coastal Studies, assessed the relationship between breaking strength of ropes and large whale entanglement. Adult whales that were entangled in gear were usually seen in ropes that had breaking strengths exceeding 5,000 pounds. The researchers surmised that larger whales were able to break free from lower breaking strength ropes before a complex entanglement resulted. Calves to two-year olds were seen entangled in gear that averaged a 2,186 pound breaking strength. The researchers suspected that these young animals entangled in gear of higher breaking strength may not have been able to reach the surface and drown or were anchored by the gear and eventually died before being detected. These hypotheses explain why young whales are not typically observed in stronger gear (Knowlton, 2012, p. 20). *Therefore, a rope's diameter, abrasiveness, and breaking strength must be considered when attempting to determine its impact on the entanglements of right whales.*

2.6 Modifications to Lobster Fishing Gear

Organizations, including the Bycatch Consortium, New England Aquarium, and Provincetown Center for Coastal Studies, work to modify gear as a means to lessen the impact entanglements have on North Atlantic right whales. In addition, the National Marine Fisheries Service created the Atlantic Large Whale Take Reduction Team in 1996. The Take Reduction Team consists of members from Maine through Florida, including fishermen, conservationists, scientists, and state and federal government representatives. They are responsible for monitoring the relationship between large whales and commercial fishing gear through the creation of a take reduction plan. The Plan was created in 1997 and aimed to decrease the frequency of large whale entanglements in lobster and gillnet fishing gear. The Team frequently aids in drafting proposed regulations: modifications to gear, reducing lines in the water column, and limiting interaction between whales and fixed fishing gear (Johnson et. al., 2007, p. 395). *Currently, the team is focused on gear modifications, both in the development process and those already tested*.

Many ideas have been proposed by all of these organizations to modify the current fishing gear. A selection of gear modification techniques can be seen in Table 1. This table is by no means a comprehensive list. "Fishing Techniques to Reduce the Bycatch of Threatened Marine Animals" by Werner et al. discusses modifications at greater lengths. We have chosen to discuss examples from three important categories of gear modification: adoption of *ropeless fishing*, incorporation of the *sensory capabilities of whales*, and alteration of *physical characteristics of ropes*.

Table 1: Categories of Fishing Gear Modifications

Category	Modification	Citation
Ropeless Fishing	Buoy-Line Trigger Release	The Large Whale Entanglement Working Group, 2008, p. 5
Sensory Capabilities of Whales	Illuminated Rope	The Large Whale Entanglement Working Group, 2008, p. 8
	Colored Rope	S. Kraus, personal communication, September 18, 2013
Physical Characteristics of Rope	Stiff Rope	Johnson et al., 2007, p. 401
	Weak Rope	Knowlton, 2012, p. 20

2.6.1 Ropeless Fishing

The Large Whale Entanglement Working Group determined that *the only solution that would eliminate entanglement entirely would be to eliminate all ropes from the water column* (The Large Whale Entanglement Working Group, 2008, p. 5). They recommend research be devoted to developing ropeless fishing gear. For example, buoy line trigger releases would keep ropes out of the water column until an acoustic signal is sent, allowing the rope and buoy that were kept on the ocean floor to surface. This option would be expensive to implement and the acoustics could interfere with the whales' ability to communicate (The Large Whale Entanglement Working Group, 2008, p. 8). This option also may not be immediately practical for the commercial fishing industry; therefore, other options have been explored.

2.6.2 Gear Modifications Incorporating the Sensory Capabilities of Whales

Whale researchers are working to alter ropes so whales can see them in the water. Sight is a whale's primary sensory behavior and may be the best way to deter whales from ropes (Johnson et al., 2007, p. 400). Illuminated rope was explored in hopes that whales could detect the ropes prior to encountering them. Researchers produced illuminated ropes, but maintaining the luminescence is difficult due to the excessive wear of ropes resulting from use in a mechanical hauler (Werner et al., 2006, p. 55). A difficulty in conducting this research includes the production of rope that remains illuminated for extended periods of time (The

Large Whale Entanglement Working Group, 2008, p. 9; Werner et al., 2006, p. 56). In addition to illuminated ropes, research is currently being carried out to determine if whales can differentiate between different colors of rope. This research began with determining that the blue, green ocean is seen as white to the whales. Orange and red have the highest contrast in their path of vision and are seen as black, while green and black provide very little contrast against the white ocean. *Preliminary data suggests that whales may be able to detect orange and red colored rope;* whereas black and green rope may blend in with the ocean (S. Kraus, personal communication, September 18, 2013). Therefore, the use of orange or red rope in vertical lines may result in avoidance behavior from whales but this study is still in progress.

2.6.3 Physical Characteristics of Rope

Two alternatives that set out to change the physical characteristics of rope are stiff rope and lower breaking strength rope. Stiff rope would prevent the rope from wrapping around a whale. However if the rope could not coil, it would be difficult for fishermen to use safely. A commercially available rope that could coil on the deck and be stiff in the water does not yet exist. Prototypes are currently in the field, but have yet to be completely successful (Johnson et al., 2007, p. 401). The second modification would be to reduce the breaking strength of the rope used. This option would ideally have the rope break at the point of contact and before the entanglement became too severe for the whale. Lobstermen have expressed concerns that this option may increase gear loss yet research has continued in aims of finding a solution that provides a safer environment for the whales and remains effective for the lobstermen (Johnson et al., 2007, p. 401).

2.7 Testing of Gear Modifications

The impact that gear modifications have on whales cannot be determined through in-field testing. Therefore, Dr. Laurens E. Howle of Bellequant Engineering is currently developing a computer simulator that would enable researchers to model North Atlantic right whale entanglement. This simulator models both North Atlantic right whales as well as gear configurations. A person using the simulator would see gear in the water column and use a video game controller to move the whale towards the gear. The goals for this simulator in the coming years are to: simulate entanglement, aid in reverse engineering to determine how whales become entangled, test various gear configurations, and generate videos for educational purposes. Currently, rope is modeled using a partial differential equation and properties including stiffness and breaking strength can be altered. This simulator could allow researchers to test ideas for gear modifications prior to implementing them in the lobster fishing industry (L. Howle, personal communication, October 4, 2013).

2.7.1 Preliminary Trials of Lower Breaking Strength Rope

Preliminary tests have been performed to determine whether lower breaking strength ropes would be a viable option for lobstermen to adopt in the vertical lines of lobster traps. The National Marine Fisheries Service assessed what breaking strengths of ropes would be necessary for effective fishing. To effectively haul offshore trawls at speeds ranging from five to ten knots, the team stated *vertical lines of lobster traps only need a breaking strength of 640 pounds*. While they acknowledged this number may be an underestimate, it is well below the breaking strength of ropes currently being used. Current vertical lines occasionally exceed breaking strengths of 5,000 pounds. Therefore, lowering the breaking strengths of ropes used in vertical lines is a promising option for modification (Knowlton et al., 2013, p. 20).

In 2006, Tim Werner, with the Consortium for Wildlife Bycatch Reduction, developed a polypropylene-barium sulfate blend rope with a breaking strength of 1,200 pounds and a diameter of 3/8 inch which was tested by ten lobstermen. Two main concerns addressed by the lobstermen were the *abrasion resistance* and the *practicality of the rope's use in existing machinery.* These obstacles could potentially be overcome with increased resistance to abrasion and increased diameter to better feed into a hauler. The lobstermen who participated in this research displayed interest in using ropes that will accommodate their needs (T. Werner, personal communication, April 11, 2013). **Our project therefore aimed to develop and test a framework with which to assess the characteristics of an alternative 1,500 pound breaking strength rope that would be safer for North Atlantic right whales and effective for lobster fishing.**

2.8 Summary

Entanglement remains a serious threat to North Atlantic right whales and was the focus of this project. While the adoption of ropeless fishing would have the largest impact on decreasing entanglement, it is not financially feasible. Therefore, fishing gear modification is currently the most promising solution to reduce the risk of entanglement. Experts agree that lower breaking strength rope is one of the most encouraging options for gear modification. The lower breaking strength rope could be implemented quickly and save the small number of whales necessary to help the population recover. Although a lower breaking strength rope has been developed, the rope failed to be feasible for lobster fishing. In conjunction with the Consortium of Wildlife Bycatch Reduction at the New England Aquarium, we investigated potential rope alternatives as well as developed a multivariable assessment tool on which to assess alternatives based on the considerations of lobstermen and needs of North Atlantic right whales.

3.0 Methodology

The goal of this project was to develop and test a framework with which to assess the characteristics of an alternative 1,500 breaking strength rope that would be safer for North Atlantic right whale and effective for lobster fishing. We developed a framework to assess the implications of new rope alternatives, as well as provided recommendations for designing a 1,500 pound breaking strength rope based on our findings. To accomplish these goals, we completed the following objectives:

1. Identified the criteria a rope should meet in order to reduce the severity and duration of entanglements of North Atlantic right whales.
2. Determined the concerns that lobstermen have about introducing a rope alternative into the commercial lobster fishing industry.
3. Investigated potential innovations in materials, manufacturing and existing ropes that could be applied to the vertical lines of lobster traps.
4. Developed and tested a multivariable assessment tool to rate potential rope alternatives based on findings from objectives one through three.

In this chapter, we discuss the steps taken in order to accomplish each objective. By accomplishing objectives one through three, we obtained the information necessary to complete objective four. In developing our multivariable assessment tool, we considered the entanglement issue from multiple perspectives: technical feasibility of introducing alternatives for vertical lines of lobster traps, safety of the whales and our ethical and legal responsibilities to them, and practical and economic concerns of the lobstermen. Incorporating these perspectives allowed us to analyze alternatives from several angles and provide appropriate recommendations that would not mask the complexity of the problem.

3.1 Identify the criteria a rope should meet in order to reduce the severity and duration of entanglements of North Atlantic right whales.

Studies suggest that different attributes of rope affect the severity and duration of entanglements (Knowlton et al., 2013, p. 19). We aimed to explore the benefits and disadvantages to the whales resulting from different characteristics of rope. We compiled this information from two sources: interviews with researchers and analysis of right whale entanglement case studies. We used the information gathered from these two sources to create a list of considerations to be used in our multivariable assessment tool conducted as part of objective four.

3.1.1 Interviews with Researchers

To understand the effects vertical lines currently being used by lobstermen have on North Atlantic right whales, we interviewed three researchers. We determined which researchers to speak with based on their experience with North Atlantic right whales, familiarity with entanglements, knowledge of past, present, and proposed gear modifications to reduce entanglement, and opportunity to meet with them. The researchers we interviewed were:

- Amy Knowlton, Research Scientist at the New England Aquarium, who has a Master's Degree in Marine Affairs and a Bachelor's Degree in Geography. She has spent 31 years working on the NEAq's Right Whale Research Project. Her focus has been on entanglements and ship strikes while educating mariners about the right whales.
- Scott Kraus, Vice President for Research at the New England Aquarium, who has a Doctorate in Zoology, a Master's Degree in Biology, and a Bachelor's Degree in Human Ecology. His focus for the NEAq's Right Whale Research Project is on the population biology and conservation. He also works on ways to reduce bycatch in fishing gear.
- Allison Henry, a member of the NEAq's Right Whale Research Project and an employee of National Oceanographic and Atmospheric Administration. She photographs right whales and documents entanglement information.

We conducted semi-structured interviews, lasting approximately one hour, with a list of questions to guide our conversations (Table 2).

Table 2: Interview Guide for Researchers

Interview Guide for Researchers

• What is your experience working with North Atlantic right whale entanglement?
• What rope research is currently ongoing?
• What are your opinions on gear modifications to reduce North Atlantic right whale entanglement?
    o Gear modifications to lessen the severity of entanglements?
    o Gear modifications to lessen the duration of entanglements?
• What is your opinion of rope release mechanisms? Mechanical? Biodegradable?
• What would have to be done to completely eliminate entanglement?
• Where do most entanglements occur? When?
• What is your opinion of the conclusion that a 1,500 pound breaking strength rope would reduce the severity and duration of the entanglements?
    o How much of an impact would it have on adults/calves/juveniles?
• What is the single most promising gear modification?

We chose to use semi-structured interviews to allow the researchers to expand upon their experiences and allow us to ask questions directly related to a specific researcher's experiences as we learned about them. Our questions targeted entanglement documentation, previous gear modifications, as well as promising developments in gear modification. We also gained insight on the reasoning behind the 1,500 pound breaking strength guideline. Interviews with researchers were recorded into a bound notebook. We summarized the key points of the interviews and used the information to support our findings. This information can be found in Appendix C.

3.1.2 Analysis of Entanglement Case Studies

To supplement the knowledge we gained through the interviews, we analyzed entanglement case studies. The entanglement case studies are the appendices to Amy Knowlton et al.'s "Implications of Fishing Gear Strength on the Severity of Large Whale Entanglement" and an example of one of the case studies can be seen in Appendix A (Knowlton et al., 2013). We only extracted the data from entanglement cases that involved the vertical lines of lobster traps (n=11). For each of these cases we recorded:

- Rope polymer
- Diameter
- Breaking strength
- Rope condition
- Severity of entanglement
- Duration of entanglement

Based on this information, we estimated the average breaking strength of vertical line rope of lobster traps that have resulted in right whale entanglement. We then compared this number to the recommended 1,500 pound breaking strength. In addition, we compared the breaking strength to the diameter of the retrieved rope. However, data regarding gear involved in entanglements is limited because removing gear from entangled whales is incredibly dangerous and gear is frequently neither removed nor identified.

We organized the information gathered from the entanglement case studies into a table, which can be seen in Appendix B. We were then able to analyze the data using statistical software, Excel. We also used this software to create graphical representations of the data we collected and analyzed.

3.2 Determine the concerns that lobstermen have about introducing a rope alternative into the commercial lobster fishing industry.

Introduction of an innovation into an industry can often face resistance; therefore, obstacles to implementation must be predicted and accounted for. In order to foresee such obstacles, we set out to discover the opinions of lobstermen about current rope and their relative importance in the commercial lobster fishing industry. These features included, but were not limited to, compatibility with current equipment, durability, likelihood to contribute to lost gear, and cost. We gained this knowledge from *interviews with lobstermen.* We also supplemented lobstermen responses by performing a *stress-strain test on rope* we collected from a lobsterman to better specify his definition of a "too weak" rope.

3.2.1 Interviews with Lobstermen

We conducted semi-structured interviews with ten lobstermen who fish in a variety of areas in Maine. We contacted Patrice McCarron, president of the Maine Lobstermen's Association, to provide us with names and contact information of lobstermen. Amy Knowlton and Bill McWeeny also aided us in establishing contact with additional lobstermen. We conducted interviews lasting 15-30 minutes either in person, over the phone, or via email. All participants signed a consent form or gave verbal consent prior to answering any of our questions. We chose semi-structured interviews in order to allow lobstermen to elaborate on their experiences as well as to account for factors of rope we had not previously considered. Our interview guide covered topics such as current rope used, fishing conditions, typical yearly gear loss, and their concerns about a 1,500 pound breaking strength rope. The complete interview guide can be seen in Appendix D. Interviews were transcribed into a bound notebook for record keeping but names and identifying information of the lobstermen were omitted to ensure confidentiality. We hoped to make contact with an additional ten lobstermen from Massachusetts; however, we did not receive responses from our contacts.

After completing the interviews, we grouped similar responses together which resulted in categories such as diameter, brand of rope, and fishing zone. In doing this, we were able to detect patterns between different aspects of rope, gear configurations, location of gear, and concerns about 1,500 pounds breaking strength rope. These patterns then allowed us to compile considerations and explanations for the considerations to be assessed in our multivariable assessment tool conducted as part of objective four.

3.2.2 Stress-Strain Testing

In addition to addressing the lobstermen's concerns regarding 1,500 pound breaking strength rope, we tested a rope a lobsterman had given us after he deemed it "too weak" to fish with. In performing a stress-strain test, we quantified a lobsterman's opinion of "too weak." Although, this single case does not allow us to generalize to all lobstermen, we consider it suggestive of lobstermen's opinions collectively. The results of the test allowed us to determine if 1,500 pounds was above or below this particular lobsterman's threshold for safe use. We performed three tests, with the help of Professor Rahbar, on samples from the same rope in a civil engineering lab at Worcester Polytechnic Institute. We placed one-foot long segments of the rope into the stress-strain machine and exerted a force until the rope broke. We obtained stress-strain curves and breaking strength values for each of the three tests. While the tests provided us with useful information, we recognize more samples would have provided us with data applicable to a wider range of lobstermen and fishing areas.

3.3 Investigate potential innovations in materials, manufacturing and existing ropes that could be applied to the vertical lines of lobster traps.

The rope currently used in the commercial lobster fishing industry contributes to the entanglement of North Atlantic right whales. To potentially decrease the duration and severity of entanglements, we considered innovations in three areas. We set out to find *materials* and *manufacturing techniques* that could produce rope alternatives with 1,500 pound breaking strength. In addition, we aimed to find *existing ropes* with 1,500 pound breaking strengths that are not marketed to the lobster fishing industry. We intended to discover at least two alternatives from each of these three categories. To establish a systematic process for collecting data about each potential alternative, we constructed a table for materials, manufacturing techniques, and existing ropes with the information we obtained. We determined what information to collect from both the literature review and responses we received from lobstermen and whale researchers regarding rope diameter, breaking strength, durability, and flexibility. Examples of these tables are found in the following three subsections.

3.3.1 Materials

We considered a material a potential alternative *if it has potential to be developed into a rope with a breaking strength in the range from 1,200 to 2,000 pounds and withstand an aquatic application*. Universities have always been at the forefront of published cutting edge technology, especially in regards to materials research (National Science Foundation, 2012). Therefore, we searched universities with materials science or materials engineering programs. *US News and World Report* ranks the top graduate programs each year and we explored their list of top materials engineering graduate schools from 2013 (US News and World Report, 2013). We investigated the ongoing research at the top 100 universities to determine if the materials being researched met our previously stated definition of an alternative. We found two materials that fit our description of an alternative material. We then emailed or called the faculty member working with that material. We contacted one professor each at University of California at San Diego and at Texas A&M University. We asked questions regarding information necessary to complete Table 3.

Table 3: Example Alternative Rope Material Characteristics Chart

Rope Characteristics	Shape Memory Alloy	Shape Memory Polymer
Production State		
Ability to be used as a vertical line in the lobster industry		
Flexibility		
Interaction with water		
Ability to work with current lobster fishing equipment		
Ability to be spliced		
Abrasion Resistance		
Breaking Strength		
Cost		
Diameter		
Specific Gravity		
UV resistance		
Additional Notes		
Material		
Manufacturing Process		

3.3.2 Manufacturing techniques

An alternative manufacturing technique would need to *alter existing ropes and provide a breaking strength ranging from 1,200 to 2,000 pounds*. Manufacturing processes have a substantial impact on the final properties of the rope (Novabraid, n.d. c). Therefore, we investigated how ropes can be processed and altered to meet desired specifications. Our investigation was conducted through online inquiries to discover manufacturers. We used the information on their websites to gather information about techniques they are currently using as well as how these affect the properties of the rope. We contacted Novabraid and Industrial Polymers Corporation about three different manufacturing techniques, specifically coatings, to gather additional information to complete Table 4.

Table 4: Example Coating Characteristics Chart

Rope Characteristics	Maxijacket Urethane Coating	TrueKote CS-100	Truecoat CS-252
Production State			
Ability to be used as a vertical line in the lobster industry			
Flexibility			
Interaction with water			
Ability to work with current equipment			
Ability to splice			
Abrasion Resistance			
Breaking Strength			
Cost			
Diameter			
Specific Gravity			
UV resistance			
Additional Notes			

3.3.3 Existing Ropes

We defined an alternative existing rope as a rope that is *not currently marketed to the lobster fishing industry but is commercially available.* We explored other sectors in the commercial fishing industry, specifically gillnet fishing. We established contact with one major rope supplier, Novabraid, that supplies to sectors outside of the lobster fishing industry. We compiled specifications of the identified ropes using the existing rope chart, Table 5, based off the information on the suppliers' websites and through communication with the supplier.

Table 5: Example Alternative Rope Characteristics Chart

Rope Characteristics	Novabraid Duraflex Lead Core	Novabraid Norpacific Gillnet Corkline High Tenacity
Production State		
Ability to be used as a vertical line in the lobster industry		
Flexibility		
Interaction with water		
Ability to work with current equipment		
Ability to splice		
Abrasion Resistance		
Breaking Strength		
Cost		
Diameter		
Specific Gravity		
UV resistance		

3.4 Develop and test a multi-dimensional assessment tool to rate potential rope alternatives based on findings from objectives one through three.

Whale entanglement is a multi-faceted problem. As stated previously, both the considerations for the safety of North Atlantic right whales and the considerations of the lobstermen must be taken into account. Therefore, we developed a framework to assess potential rope alternatives that is also multi-faceted. To accomplish this, we used Multi-Attribute Utility Theory (MAUT) (Tzeng and Huang, 2011, p. 194). MAUT is a multiple-criteria decision-making tool that is specifically useful for identifying solutions that must meet multiple constraints such as risk management when a high level of uncertainty is involved (Tzeng and Huang, 2011, p. 194).

In MAUT, *alternatives* are assessed on a variety of criteria called *considerations*. Considerations can include factors such as cost and safety. These considerations are assigned a *weight* which indicates their importance to the situation being investigated. Different individuals may assign different weightings dependent on their personal value of that consideration. Alternatives are assigned *scores* based on how well they meet these given considerations. Scores are multiplied by the weight of that consideration and then these products are summed for each alternative. MAUT is useful in this project given that we need to take into account a variety of different perspectives including the safety of the whales, perspectives within the lobster fishing industry, and available technology when analyzing alternatives.

We used the following procedure to analyze alternative technologies:

3.4.1 Identifying the Considerations

We determined what characteristics of rope were important to various stakeholders and therefore were necessary to include in our multivariable assessment tool based on our findings from objective one and two. These characteristics are defined in methodology of MAUT as *considerations*. An example consideration we determined is the diameter of a rope.

3.4.2 Weighting the Considerations

First, the relative importance of each consideration was assessed. Each consideration was given two relative importance weightings, one for the importance to the lobster fishing industry and a second for the safety of the North Atlantic right whales. The importance weighting is based off of how much impact the consideration would have on the lobster fishing industry or the North Atlantic right whales. The rating system for relative importance is pictured in Table 6.

Table 6: Considerations Weighting Method

Weighting	Relative Importance
2	High
1	Moderate
0	None

We determined the weightings based off of information we received in objectives one and two and our literature review. The two relative importance weightings were then summed to give the overall importance score. Therefore, a scale for overall weighting of 0-4 was used with 0 being *of no importance to either group* and 4 being *of great importance to both groups.* The weighting process is a critical step because some considerations are more influential to the overall problem than others and this influence needs to be reflected in the assessment of alternatives. For our example consideration, diameter received a weighting of 2 for its high importance to the lobster fishing industry and a weighting of 2 for its importance to protect North Atlantic right whales. Therefore, the example consideration’s total weighting is 4.

3.4.3 Scoring the Alternatives

The rope alternatives (materials, manufacturing techniques, and alternative ropes) from objective three were listed in a separate column in the worksheet. Each *alternative* was given a score on each consideration using a scale of 1 to 3. A "3" is defined as *exceeds the consideration* while a "1" is defined as *does not meet the consideration*. A score of "2" is neutral, defining the alternative as satisfying that consideration. We assigned scores based on the knowledge we gained in the first three objectives and through our literature review. The scoring system we used is presented in Table 7.

Table 7: Alternatives Scoring Method

Score	Significance of Scores
3	Exceeds
2	Meets
1	Does Not Meet

If we were to assess a rope, "Rope X", on its ability to meet our example consideration of diameter we would give it a score of 1, if it could not be produced with a desirable diameter. We would assign Rope X a 2, if it could be produced with a desirable diameter. We would assign Rope X a 3, if it could be produce with a customizable diameter.

3.4.4 Calculating the Decision

The decision is defined in the MAUT methodology as giving each alternative a *score*. The score is calculated by multiplying the weight for each consideration (0 to 4) by the score for each consideration (1 to 3). These products are then summed to find the *total assessment score* for each alternative. Alternatives with higher scores are typically defined as better *decisions*. For our example consideration, if Rope X received a score of 2 for diameter, it would be multiplied by the weight of diameter (4) for a total score of 8.

However, low scores can result from a lack of knowledge for some considerations. Therefore, a total assessment score for alternatives could only be calculated in part. We took this into account by performing the additional step of assigning an uncertainty rating (Table 8). If we could score an alternative on greater than 11 considerations, it had a low uncertainty rating. If we could score an alternative on 6-10 considerations, it had a moderate uncertainty rating. If we could score an alternative on 1-5 considerations, it had a high uncertainty rating. These uncertainty ratings allowed us to better understand the limitations of the score.

Table 8: Uncertainty Rating Scale

Uncertainty Rating	Number of Considerations Assessed
Low	$\geq$ 11
Moderate	6 - 10
High	1 - 5

Discussion of materials, coatings, and existing ropes as well as the relevant perspectives of both the North Atlantic right whales and lobstermen can be found in the Findings chapter. The execution of our multivariable assessment tool and its implications are explained in the Discussion chapter.

4.0 Findings

In this chapter, we will discuss the results of our first three objectives. We will present the considerations we found important to ensure the safety of North Atlantic right whales and the needs of lobstermen. We also discuss findings related to the specifications of rope alternatives, including materials, coatings, and existing rope.

4.1 Considerations

Finding #1: Breaking strength of vertical line rope is an important factor when considering the safety of North Atlantic right whales.

Through interviews with researchers and analysis of lobster gear related North Atlantic right whale entanglement case studies, we identified breaking strength as an important feature of rope when trying to protect North Atlantic right whales. Implementing lower breaking strength rope would not require significant changes to the lobster fishing as a whole and has the potential to save whales from fatal entanglements.

Lower breaking strength rope is considered one of the most promising gear modification techniques, according to the researchers we interviewed. We supported this claim through analysis of vertical line entanglement case studies. Of the entanglement case studies that were confirmed to involve vertical lines of lobster traps (n=11), the average tested breaking strength of the ropes involved in entanglement was 2,274 pounds (n=20). The median tested breaking strength was 1,863 pounds. We calculated the median to minimize the effect the outliers had on the average breaking strength. Both the average and the median of the tested breaking strength are greater than our goal of a 1,500 pound breaking strength rope. Since only one adult whale was found entangled in vertical line rope with a breaking strength less than 1,500 pounds, the entanglement case study data suggests a 1,500 pound breaking strength rope would reduce the severity and duration of North Atlantic right whale entanglements (Knowlton et al., 2013).

Finding #2: The diameter of the vertical line rope is inversely proportional to the extent of North Atlantic right whale injury.

Entanglements occur regardless of the diameter of the rope involved in the entanglements but *diameter may mitigate entanglement severity.* In a study conducted by Jeremy Winn, entanglements were simulated on deceased whale flippers (Winn et al., 2008, p. 340). He concluded 1/4 inch diameter rope cut significantly deeper into whale skin than 3/8 inch diameter rope. On the basis of this study, it is widely accepted that a smaller diameter rope would increase the injury to whale, while a larger diameter rope would decrease the extent of whale injury. Winn stated that “gear modifications that can help to minimize the penetration of the epidermis are of high priority” (Winn et al., 2008, p. 331).

In our interviews, researchers suggested diameter may mitigate entanglement severity. However, when we performed statistical analysis on the diameter and severity data from the entanglement case studies, the correlation between the two was not statistically significant. Ropes would need to be retrieved and analyzed from more entanglement case studies to better establish this relationship. However, the results from the experiments performed by Jeremy

Winn provide sufficient evidence to justify including diameter as a consideration, when modifying rope that would positively impact North Atlantic right whales.

Finding #3: Diameter of the vertical line rope is directly proportional to the breaking strength.

The data regarding vertical lines of lobster traps extrapolated from the entanglement studies indicate that diameter is directly proportional to breaking strength (correlation coefficient= 0.669). As diameter increases, breaking strength also increases as shown in Figure 6. If current manufacturing techniques could be altered so a larger diameter did not result in a rope with an increased breaking strength, there would be potential to create a safer rope for North Atlantic right whales that has a large diameter but a low breaking strength.

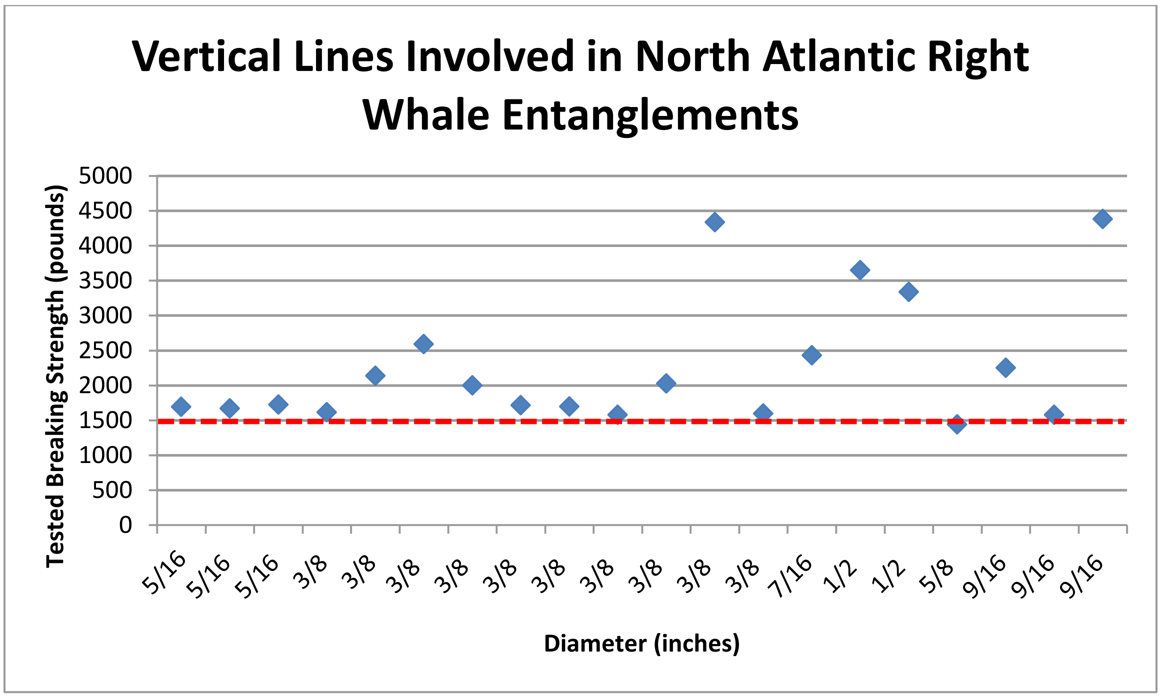

Figure 6: Plot comparing tested breaking strength versus diameter retrieved from North Atlantic right whale entanglements

While the data set is limited (n=20), only a single adult whale was found entangled in vertical line rope with a breaking strength of less than 1,500 pounds. These data began to suggest that *1,500 pounds is below the breaking strength of rope typically observed in entanglements involving the vertical lines of lobster pots.*

Finding #4: Durability is one of the most important factors considered when lobstermen choose rope to use for the vertical lines of lobster traps.

After conducting interviews with ten lobstermen from various areas in Maine, we learned that all of them noted durability as an important factor when selecting a vertical line. A summary of these interviews can be seen in Appendix E. Ropes used exclusively for vertical lines normally last around three years according to the interviewees with a little variance given how active the lobstermen were. According to one lobsterman, “if the rope is not real consistent, it wouldn't be long before it becomes 1,000 pound (breaking strength) and then you would have to tie and it would be a real small breaking strength."

We identified four main factors that affect durability in vertical lines from our interviews. We supplemented the information from our interviews with our previous background research:

- **UV light:** One lobsterman stores his rope under a cover that protects it from sunlight. He claims that his rope lasts five to six years, which is longer than the average we identified as four years. The four year lifespan is a result of other lobstermen storing their rope outside. Prolonged exposure to sunlight increases the likelihood that a plastic will fracture on impact (Schoolenberg, 1988).
- **Interaction with the marine environment**: Rope degrades by exposure to salt water and biological agents (Lefebvre and Moletta, 2006, p. 1). Some interviewees stated this causes the rope to "rot."
- **Forces exerted by the hauler:** The hauler mechanism exerts significant force on the surface on the rope and degrades the surface significantly each time the rope passes through it. A lobsterman stated that the "hauler just destroys the rope" and a rope must be able to withstand the rigorous use in the hauler.
- **Fishing location:** Some lobstermen primarily fish in rocky bottom areas while other primarily fish in muddy bottom areas. When rope gets stuck in the rocky bottom this slices the rope and could break it. One lobsterman stated that this can cause the rope to become frayed and that "lower breaking strength would not be safe for rocky bottom."

Finding #5: Lobstermen who fish in muddy bottom areas reacted more positively to the idea of a 1,500 pound breaking strength rope than those who fish in rocky bottom areas.

Of the ten lobstermen we interviewed, many of them explained that the fishing conditions they face along the coast of Maine are highly variable.

Fishing in muddy bottoms

Lobstermen who fish in muddy bottoms believe a reduction in breaking strength of their vertical line to 1,500 pounds would not be a problem. We found a lobsterman who currently uses a 1,100 pound breaking strength rope; therefore, a 1,500 pound breaking strength rope would be an increase in strength for him. Another lobsterman didn't "think 1,500 pound breaking strength would be an issue with hauling doubles [a gear configuration with one vertical line for every two traps]."

Fishing in rocky bottoms

In comparison to muddy bottoms, rocky bottoms impose much harsher fishing conditions. The general consensus amongst lobstermen who fish in rocky bottom areas was that a lower breaking strength would not work. One stated that "We've dismissed it, never seemed feasible at all." This lobsterman supported this statement by saying, "current gear snaps as it is, doesn't happen a lot but we all lose gear that way." Breaking strength typically was mentioned as a concern when speaking about less frequent incidences such as storms, unusually strong tides, or when gear becomes caught on rocks or other gear, *not* necessarily as a concern for everyday fishing. Another lobsterman explained how he "could sometimes break 3,700 pound breaking strength rope." Therefore, a decrease in breaking strength could lead to more gear loss. Furthermore, we also learned that rocky bottoms pose a safety concern for the lobstermen when the rope gets caught on a rock. A lower breaking strength rope could snap and prevent the boat from capsizing.

Finding #6: 1,500 pounds is greater than the breaking strength of rope a lobsterman considered too weak for fishing.

We concluded that breaking strength is a major concern amongst lobstermen in all areas. However, a major challenge we had in conducting the interviews was half of the lobstermen did not know what breaking strength they currently used for their vertical lines. Therefore, some of them had no baseline to compare 1,500 pound breaking strength rope with and quickly dismissed the idea. The lobstermen who did know what their rope's breaking strength cited breaking strengths ranging from 1,100 to 3,700 pounds.

In one interview, the lobsterman gave us a rope that he deemed too weak to continue hauling in traps with because of fear that it would break. This lobsterman fishes mainly in rocky bottom areas with two traps per vertical line. The rope seen in Figure 7 had an initial, purchased diameter of 3/8 inch but a measured 7/20 inch diameter with obvious signs of wear.

Figure 7: Used vertical line from a lobster trap on table and in tensile strength machine (Tyler Ewing)

A lab manager positioned the rope into the tensile strength machine and tested its maximum breaking strength. The resulting stress-strain curve can be seen in Figure 8.

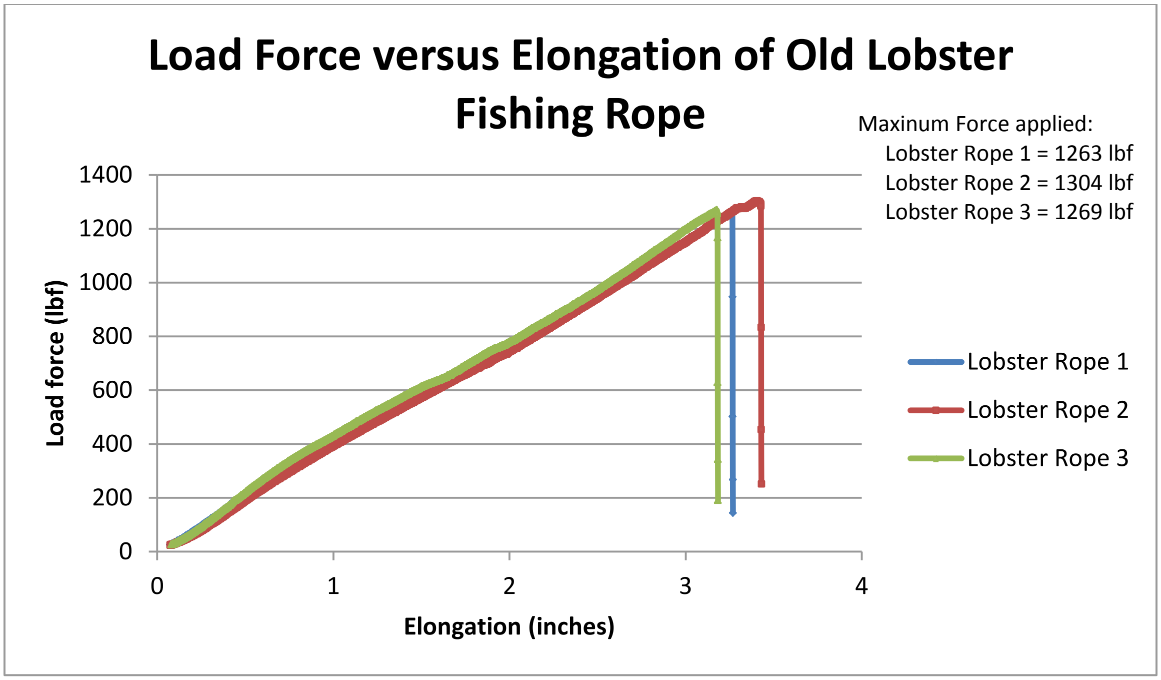

Figure 8: Load versus elongation of the rope and maximum breaking strength

Of the three tests conducted, the breaking strengths of the rope ranged from 1,263 pounds to 1,304 pounds with the average breaking strength being 1,279 pounds. This rope's average breaking strength was 221 pounds below the proposed 1,500 pound breaking strength. This result indicates the potential of fishing with a 1,500 pound breaking strength rope in rocky bottom areas. However, this observation was based on a single rope. To draw stronger conclusions, similar studies on a wider array for ropes are necessary.

Finding #7: Lobstermen have concerns about their rope's operational and safety specifications.

Diameter of a rope greatly affects the operational and safety specifications for the lobstermen. For example, diameter affects how the rope feeds into the hauler. The hauler is an essential piece of lobster fishing equipment used to haul up the traps by pulling in the vertical line. Five lobstermen mentioned that any alternative must be compatible with their hauler. Significantly different diameters need different hauler configurations. Rope diameter varied greatly in the interviews from 11/32 inches to 5/8 inches. However, 7/16 inches was mentioned by seven lobstermen as one of the diameters they used. Eight lobstermen said they used ropes with varying diameters, depending on various conditions. Changing the configuration of the hauler requires significant time and money for the lobstermen. The way rope behaves in the hauler is also an important safety aspect for the lobstermen. As the rope comes out of the hauler, it should ideally coil neatly in order to keep the rope contained. Insufficient coiling is a safety hazard for the lobsterman onboard.

Another operational concern lobstermen expressed was whether vertical line rope meets regulations. There are many regulations put in place that lobstermen must follow. The most relevant regulation to this project is the regulation mandating that the top 1/3 of a vertical line must be sinking rope outside of three nautical miles. Therefore, all offshore and some inshore lobstermen we interviewed insist that any alternative complies with the sinking rope regulation.

Finding #8: Rope replacement costs are high for lobstermen; therefore, cost is of great concern to them.

Lobstermen have high yearly vertical line rope replacement costs, as revealed in our interviews. Rope coils cost around $130 each and the lobstermen we interviewed spent from $12,000 to $15,000 on vertical line rope per year. Lobstermen use the vertical line to haul up their gear (Figure 4 in section 2.5). If something causes the vertical line to snap or break, gear may be lost, increasing lobstermen's replacement costs. Two lobstermen stated that they lost 20% of their gear per year, while the remaining eight estimated their losses at approximately 10% of their total gear per year. Gear loss can cost the average lobstermen anywhere from $3,000 to $12,000 per year.

These findings allowed us to compile the following list of considerations to be used in our multivariable assessment tool, seen in Table 9.

Table 9: List of Considerations used in our Multivariable Assessment Tool

Considerations
Ability to be readily produced for the lobster fishing industry
Ability to be used in muddy bottoms
Ability to be used in rocky bottoms
Ability to coil
Ability to handle when wet
Ability to resist wear in hauler
Ability to splice the rope
Abrasiveness
1,500 pound Breaking Strength
Cost compared to current ropes
Degradation of breaking strength
Diameter
Specific Gravity
UV resistance

4.2 Alternatives

In addition to findings regarding considerations of the lobstermen and whale researchers, we found two materials, three coatings, and two existing ropes that met our definition of alternatives. We gathered information about the alternatives by reviewing research publications by professionals in academia, searching through polymer manufactures websites, and locating rope manufacturers and suppliers' catalogs and websites. These alternatives offer potential solutions that can benefit both lobstermen and the North Atlantic right whale species.

Finding #9: Shape memory materials have the potential to be an alternative material for lobster fishing ropes.

Shape memory materials are a developing area in material science. These materials have the ability to be "programmed" to a specific shape which the user can set. After the material is programmed, it can have two phases. In the martensite phase it can be bent, twisted, or mangled into any position. When the shape memory material is subjected to certain conditions, it will revert back to its programmed position known as the austenite phase (Texas A&M, n.d.). These conditions are not the same for every material but the reacting factor is always temperature. The temperature at which the material transitions from one phase to another is called the switching temperature. Since the switching temperatures are dependent on the composition of the material, material scientists can customize the alloy to better suit a desired environment.

Shape memory materials also have the ability to be programmed into any desired shape or orientation by realigning the material's atomic structure (Lin, 2008). This realignment can be done easily by adjusting how the material is produced. After the material is extruded into a strand, it can be programmed. The programming process typically consists of placing the strand in a jig which orients it into a desired position and then running an electric current through the strand.

After reviewing the capabilities of smart memory materials, we determined that they could work well in conjunction with lower breaking strength rope. With further research, we discovered shape memory metal alloys and shape memory polymers, two types of shape memory materials, that could be applicable to this project's problem. By weaving these materials into a rope, it could be possible to create a vertical line with a 1,500 pound breaking strength for a lobster trap that would be programmed to coil when removed from the water. The materials could be programmed to change phases based on the temperature between the ambient air and water but specifics would have to be further investigated. We will discuss shape memory alloys and shape memory polymers in further detail.

First, *shape memory metal alloys* (SMAs) are specific alloys of copper, aluminum, nickel, zinc, iron, manganese, or silicon which are manufactured into wires ranging from 0.075mm to 1.25mm in diameter (Lin, 2008). With a range of wire sizes, alloys could be manufactured to mimic the diameters of the plastic fibers currently used in the vertical line of lobster traps. By doing this, the metal alloy strand would be able to be twisted into the rope without changing many of the rope's physical characteristics. In addition, the ratio of SMA strands to plastic fibers could be easily altered during the manufacturing process, allowing the stiffness of the submerged rope to be customized to meet the needs of both North Atlantic right whale survival and lobster fishing practices (Lin, 2008). While this material seems futuristic, we found that different varieties of smart memory alloys are currently being mass-produced. A nickel-titanium alloy is currently used as the underwire in women's bras today and is popular in Japan (Stoeckel, 1991, p. 50). By using shape memory alloys in this application, the underwire will never lose its shape regardless of how many times it is washed. There are still many unknowns about shape memory alloys but a summary of their properties can be seen in Appendix F.

Second, *shape memory polymers* (SMPs) were explored by researchers from Texas A&M, NASA, and Stanford University who reproduced the shape memory effect with polymers. The polymers have the same ability to be "programmed", become flexible in the martensite phase and revert back to its programmed shape in the austenite phase. However, a limitation with SMPs is lag time between phase changes. The time between phase changes depends heavily on the chemical composition of the material and in some cases the phase change can last up to 35 seconds (Lendlein and Kelch, 2002, p. 2037). The process of programming a shape memory polymer also varies from SMAs. Instead of adding an electric current to the strand, the material is heated well above the switching temperature and then cooled back down to the martensite phase. Currently, applications for the SMP technology are limited to the medical field (Sokolowski, 2005, p. 1). Nevertheless, there are many attractive characteristics of SMPs that would make them practical for the lobster fishing industry. The polymers can be extruded into fibers, allowing for the possibility of being processed into a synthetic fiber rope (Sokolowski, 2005, p. 4). These polymers also have a wider range of switching temperatures, ranging from -70°C to +70°C (Sokolowski, 2005, p. 4). The wider temperature range allows material scientists to customize the material even more than SMAs, possibly making it available for a vast variety of uses. The costs to manufacture these polymers are much cheaper than smart memory alloys as well. In most cases, the production of smart memory polymers is 10% of the cost of producing a comparable metal alloy (Sokolowski, 2005, p. 4). A summary of shape memory polymer properties can be seen in Appendix F.

Finding #10: The addition of a coating to a vertical line rope with a breaking strength of 1,500 pounds could make the vertical line rope more appealing to lobstermen and less harmful to North Atlantic right whales.

Coatings are synthetic liquids that are applied to a finished rope to create a barrier around the rope. The purpose of applying a coating is to enhance some of the rope's characteristics, such as durability and abrasiveness. The coatings can also be applied in a range of thicknesses depending on the viscosity of the coating and cure time. This process helps modify thinner ropes for applications where larger diameters are needed. Coatings can also affect other rope properties such as decrease the abrasiveness, increase the lifespan, and alter the appearance. As a result, we believe that applying coatings to lower breaking strength rope could increase the rope's appeal to the lobster fishing industry and be beneficial for North Atlantic right whales.

From reviewing manufacturers' websites and online inquiries, we were able to find three coating options that may be viable additions to lower breaking strength rope:

1) *Maxijacket Urethane Coating*

Maxijacket Urethane coating is produced by Yale Cordage who markets it towards synthetic fiber ropes. Maxijacket is a water-based, urethane coating which is thin once applied to a rope. Since the coating is thin, it only changes the diameter by a small amount. This coating can also improve a rope's abrasiveness. By improving the abrasiveness, the rope could become easier to handle and reduce the likelihood of snagging on underwater rocks and debris. Maxijacket also has the ability to act as a shield for ultra violet light, decreasing the chance of fibers fraying as they age (Yale Cordage, n.d.). This ability could increase the durability and lifespan of a lower breaking strength rope.

Maxijacket Urethane coating also does not impede the workability of a rope because it does not hinder the lobstermen's ability to splice the rope. In the lobster fishing industry, it is common for lobstermen to join separate pieces of rope together with a splice. Splicing involves connecting the fibers from different ropes together to form a joint. Since Maxijacket has a thin, water based composition, lobstermen could splice ropes that have been treated with the Maxijacket urethane coating together (Yale Cordage, n.d.).

If a lower breaking strength rope is produced that has undesirable physical properties such as a short lifespan or high abrasive properties, this coating has the potential to rectify those problems. Addressing those problems could make the rope more appealing to the lobster fishing industry. Maxijacket does not alter the breaking strength of the rope it is applied to. Therefore could be applied to a lower breaking strength rope. A summary of the information collected about Maxijacket Urethane Coating can be found in Appendix G.

2) *TrueKote CS-100*

TrueKote CS-100, produced by Industrial Polymer Corporation, has many differences from the Maxijacket urethane coating. TrueKote is a much thicker, rubber based coating which increases the diameter of the rope. This coating can also be recoated, thus making the final diameter of a rope customizable (Industrial Polymer Corporation, 2003). This recoating ability could allow a rope with a lower breaking strength and smaller diameter to become viable for the lobster fishing industry and less harmful to North Atlantic right whales by applying multiple coatings until a desired diameter is reached. Additional details for TrueKote CS-100 can be found in Appendix H.

Even with an increased diameter, the coating's rubber-like properties allow the rope to remain flexible and workable. TrueKote creates a non-abrasive surface, making it easy to handle and work with. In addition, the coating only absorbs a small amount of water, protecting the core part of the rope from the ocean elements. By sealing the core strength component of the rope with a thicker shell, the rope will degrade slower than exposed rope. In addition, lobstermen could submit their rope to be refurbished when they feel their coating has become excessively worn (Industrial Polymer Corporation, 2003). Refurbishing could ultimately increase the lifespan of a 1,500 pound breaking strength rope and reduce yearly expenses as well as potentially lower replacement costs.

TrueKote is currently used to coat larger diameter ropes such as ones used to anchor large ships into port. However, this coating could be applied to smaller ropes. According to the TrueKote datasheet, the coating is fully compatible with a range of synthetic fibers which are currently used with ropes for the lobster fishing industry (Industrial Polymer Corporation, 2003). A summary of the information collected about TrueKoteCS-100 is provided in Appendix G.

3) *Truecoat CS-252*

Truecoat CS-252, a variation of TrueKote CS-100 and also produced by Industrial Polymer Corporation, is a potential lower breaking strength rope alternative for the lobster fishing industry. This coating is similar to other rubber coatings due to its urethane elastomer composition, which gives the coating the ability to be layered during the manufacturing process to match any desired diameter. According to the data sheet in Appendix I, changing the amount of time the coating cures to the rope can change the resulting diameter (Industrial Polymer Corporation, 2011). With Truecoat, the rope will remain flexible even with an increase in diameter. Just like TrueKote CS-100, this coating presents an opportunity to use a smaller diameter, lower breaking strength rope by applying a thick coating to the rope to increase the diameter. Truecoat also creates a non-abrasive surface, making it easier to handle (Industrial Polymer Corporation, 2011). When the coating is applied to a rope, the rope becomes sealed, isolating it from harsh oceanic conditions. The rope's durability and lifespan could improve by keeping water from degrading parts of the rope and protecting it from ultraviolet light. One of Truecoat's most attractive features is its chemical resistance to salt water. The coating will not degrade while submerged in the ocean for any length of time. In addition, if the coating starts to wear off, the coating has the potential to be refurbished (Industrial Polymer Corporation, 2011). Refurbishing could increase the lifespan of a lower breaking strength rope and potentially lower replacement costs for lobstermen. The Truecoat CS-252 coating is currently produced for a variety of industries, including flexible bumpers and impact resistance pads. The coating is also compatible with polymer ropes (Industrial Polymer Corporation, 2011). Many of the characteristics of the Truecoat CS-252 coating could make it an excellent lower breaking strength alternative for the lobster fishing industry. A summary of the information collected is provided in Appendix G.

Finding #11: There are existing ropes that could serve as alternatives for lower breaking strength rope in the lobster fishing industry.

The cordage industry supplies ropes to businesses around the world, ranging from the fishing industry to rock climbing. By reviewing manufacturers' and suppliers' websites and catalogs, we found two ropes that met our definition of an alternative. The alternatives we discovered are used in the fishing industry but not in lobster fishing. They are:

1) *Duraflex Lead Core*

The Duraflex Lead Core rope, manufactured by Novabraid, has an inner core that carries the majority of the force with an outer sleeve to protect this core. In a Duraflex

Lead Core rope, there is a lead strand that is crimped at regular intervals in order to have a specific tensile strength. A 5/16 inch diameter rope has a breaking strength of 1,700 pounds and a 3/8 diameter has a breaking strength of 2,000 pounds. This tensile strength allowed us to classify this rope as an alternative lower breaking strength rope (Novabraid, n.d. a). It may be possible to adjust the size of the lead crimps to lower the breaking strength for specific rope diameters. To protect the lead core, there is a braided polypropylene and polyester sleeve. This sleeve allows the rope to have a low abrasiveness. Therefore, the rope is easy to work with and handle. Since lead is a malleable metal at most temperatures, the rope remains flexible. Its flexibility allows it to be used in a hauler and on the deck of the boat. However, due to the fact that lead is a fairly heavy metal, this rope is considerably heavier than current rope in the lobster fishing industry. For a 3/8 inch diameter, 600 foot reel, the lead rope weighs a total of 65 pounds (Novabraid, n.d. a). In comparison, a 600 foot reel of 3/8 inch diameter of Polysteel weighs 37 pounds (Polysteel Atlantic ltd., 2005). However, lead is marine toxic and could negatively impact the marine environment. The braided sleeve, used to protect the lead core, increases the lifespan of the rope. The polyester and polypropylene fibers used in the sleeve are ultra violet resistant and protect the rope from the sun for long periods of time. Currently, this rope is produced for gillnet fisheries in the Northeast part of the United States and could be used in the lobster fishing industry as a lower breaking strength rope (Novabraid, n.d. a). A summary of information collected about Duraflex Lead Core rope is provided in Appendix J.

2) *Norpacific Gillnet Corkline High Tenacity*

Norpacific Gillnet Corkline High Tenacity rope, also manufactured by Novabraid, could provide an alternative lower breaking strength rope for the lobster fishing industry. This rope uses the same rope structure as the lead core rope. With Gillnet Corkline, however, the core is constructed out of a high tenacity polyester parallel strand. This core is then surrounded by a braided polyester sleeve. This sleeve is UV resistant and has a non-abrasive surface, making the rope easy to handle (Novabraid n.d. b). The load bearing core also has a lower breaking strength than typical twisted rope, allowing this rope to be a feasible alternative for this project. When the diameter is 3/8 inch, this rope has a 1,465 pound breaking strength. Due to its plastic parallel strand core, this rope is also a lightweight alternative, only weighing 8.4 pounds per 600 feet (Novabraid, n.d. b). This rope is currently marketed towards the gillnet fishing industry on the Pacific coast of the United States (Novabraid, n.d. b). Therefore, this rope is not currently used in a similar oceanic environment, but it still displays many key characteristics needed for a lower breaking strength rope. A summary of the information collected about Norpacific Gillnet Corkline rope is provided in Appendix J.

The alternatives we discussed above will be assessed using our multivariable assessment tool on the considerations presented previously in Table 8. This will allow us to incorporate the perspectives of lobstermen and whale researchers when assessing alternatives. The results of using the multivariable assessment tool will be discussed in the following chapter.

5.0 Discussion

In this chapter, we discuss the development and testing of our multivariable assessment tool. We explain the usefulness of this tool as well as how we assessed each alternative we discovered.

Finding #12: Our multivariable assessment tool is an effective method when assessing rope alternatives because it incorporates all of the perspectives relevant to lessening the extent and severity of North Atlantic right whale entanglement.

Our multivariable assessment tool is an effective method to evaluate rope alternatives. We defined effective as able to provide quantifiable recommendations for future research and implementation of alternative 1,500 pound breaking strength rope. To develop a rope alternative that has the potential to be successfully implemented, the development process must incorporate the input of all relevant stakeholders. These stakeholders would be directly affected by an alternative and would only be open to an alternative that they feel incorporates their opinions. Our tool ensures that these opinions are incorporated as considerations. The alternative is then assessed to determine whether it meets their considerations. Assessing the alternatives before pursuing them is important to ensure that perspectives of all relevant stakeholders are acknowledged. Here, we will speak about the steps we took to apply our multivariable assessment tool to this project.

5.1 Weighting the Considerations

We developed a list of considerations in our Findings Chapter. As explained in our Methodology chapter, each consideration we identified was assigned a weight that represented both the relative importance to lobstermen and the safety of North Atlantic right whales. These considerations can be seen in Table 10.

Table 10: Considerations Based on Findings from Objective One and Objective Two

Considerations
Ability to be readily produced for the lobster fishing industry
Ability to be used in muddy bottoms
Ability to be used in rocky bottoms
Ability to coil
Ability to handle when wet
Ability to resist wear in hauler
Ability to splice the rope
Abrasiveness
1,500 pound Breaking Strength
Cost compared to current ropes
Degradation of breaking strength
Diameter
Specific Gravity
UV resistance

Here, we provide justification for the weight of each consideration. These weights are based on our limited knowledge and could be altered in future applications of this tool if more knowledge is acquired. The weighting scale is provided again in Table 10.

Table 11: Weighing Scale Used To Weight Our Considerations

Rating	Relative Importance
2	High
1	Moderate
0	None

<u>Ability to be Readily Produced</u>
This consideration encompasses how quickly an alternative could be implemented into the lobster fishing industry.

Lobstermen Rating: 1
If an alternative is determined effective after this testing, an improvement to the lobstermen's current rope could be introduced sooner. Therefore, we decided it would have a moderate impact.

Whale Rating: 1
The sooner a rope could be produced, the sooner the potential implementation time could be. The sooner a safer rope could be produced, the sooner a positive impact might be seen on the whales.

Total Weight: 2

<u>Ability to be Used in Muddy Bottoms</u>
This consideration refers to how well an alternative could withstand the conditions presented by muddy bottoms.

Lobstermen Rating: 2
Many lobstermen and whale researchers expressed that no single alternative would be effective in all fishing areas and locations. Muddy bottom areas seemed to require lower breaking strength ropes since the ocean floor is less harsh on ropes.

Whale Rating: 1
Whales are found in both muddy and rocky bottom areas, regardless of the ropes used there.

Total Weight: 3

<u>Ability to be Used in Rocky Bottoms</u>
This consideration entails how well an alternative could withstand the conditions presented by rocky bottoms.

Lobstermen Rating: 2
Many lobstermen and whale researchers expressed that no single alternative would be effective in all fishing areas and locations. Lobstermen who we interviewed expressed that rocky bottom areas require higher breaking strength ropes that are more durable since the ocean floor is harsher on ropes.

Whale Rating: 1
Whales are found in both rocky and muddy bottom areas, regardless of the ropes used there.

Total Weight: 3

Ability to Coil

This consideration encompasses the ability of a rope to coil neatly after coming out of the hauler on board a lobsterman's boat.

Lobstermen Rating: 2

If rope does not coil on the surface of the boat after going through the hauler, the lobstermen can trip over the rope and this poses a significant safety risk to the lobstermen. Lobstermen would not want to adopt a rope that may not be safe.

Whales Rating: 0

The way rope behaves on board a boat does not affect the safety of North Atlantic right whales

Total Weight: 2

Ability to Handle When Wet

This consideration entails the performance of the alternative when subjected to an aquatic environment.

Lobstermen Rating: 1

This was not mentioned by the majority of lobstermen in interviews but any rope used would have to withstand an aquatic application and be easily handled by lobstermen. Rope that handles well may be adopted by lobstermen.

Whale Rating: 0

Whales would not handle ropes.

Total Weight: 1

Ability to Withstand Wear in Hauler

This consideration refers to the how well the alternative maintains it original condition after being repeatedly used in the hauler on board a lobsterman's boat.

Lobstermen Rating: 2

Rope's ability to withstand forces by the hauler is essential to lobstermen. A rope that is not damaged through use in a hauler would have an increased lifespan and would decrease a lobsterman's replacement rope costs, which we have identified as high. Ropes that do not need frequent replacing would lower lobstermen's expenses.

Whale Rating: 0

The way rope handles forces exerted by the hauler does not directly affect the safety of North Atlantic right whale.

Total Weight: 2

Ability to Splice the Rope

This consideration encompasses how well an alternative would be able to be spliced.

Lobstermen Rating: 1

Splicing is a common practice, but was not mentioned by majority of the lobstermen. They splice ropes together to salvage rope that has worn unevenly.

Whale Rating: 1

If lobstermen could not splice the rope, he would have to knot it. When a rope is knotted, the risk of the rope being entangled in a whale's baleen is increased.

Total Weight: 2

Abrasiveness

This consideration refers to whether the surface of an alternative is rough or smooth.

Lobstermen Rating: 2

Lobstermen need a rope that is not abrasive on their hands so that they can handle it when they haul in the traps.

Whale Rating: 2

In the study conducted by Jeremy Winn, rope that was more abrasive had a higher cutting power into the whale flipper (Winn et al., 2008, p. 340).

Total Weight: 4

Breaking Strength

This consideration entails whether or not an alternative can be produced with a breaking strength of 1,500 pounds.

Lobstermen Rating: 2

Although there was a difference in opinions of the 1,500 pound breaking strength rope between the interviewed lobstermen who fished inshore and who fished offshore, all of the lobstermen expressed that the breaking strength must be sufficient for them to fish with.

Whale Rating: 2

A lower breaking strength may decrease the duration and severity of North Atlantic right whale entanglements. A rope with a lower breaking strength may even prevent the entanglements before they occur.

Total Weight: 4

Cost Compared to Current Lobster Fishing Ropes

This consideration compares the cost of an alternative to the cost of current lobster fishing ropes.

Lobstermen Rating: 2

Most of the lobstermen we spoke to explained to us their high rope replacement costs. In addition, in our interview with Scott Kraus, he mentioned to us that economics are an important factor when implementing gear modifications (S. Kraus, personal communication, September 18, 2013).

Whale Rating: 0

Cost is of no concern to North Atlantic right whale entanglements.

Total Weight: 2

Degradation of Breaking Strength

This consideration indicates if an alternative retains its breaking strength over time.

Lobstermen Rating: 2

How quickly or slowly the breaking strength of a rope degrades affects the lifespan of the rope. If an alternative was to increase the degradation of the breaking strength, replacement costs may increase for lobstermen. In addition, the rope must maintain its breaking strength to continue to be effective for hauling in traps.

Whale Rating: 1

The duration and severity of North Atlantic right whale entanglements may decrease with weaker rope. However, if the degradation of an alternative is slow but has a starting breaking strength of 1,500 pounds, it would not be significantly detrimental to the right whales.

Total Weight: 3

Diameter

This consideration encompasses an alternative's ability to be produced with an appropriate diameter.

Lobstermen Rating: 2

Most of the lobstermen we spoke to expressed the importance of having a rope with a diameter that is compatible with their hauler. In addition, if the diameter is too large, more drag can be exerted on the vertical line when tides are high.

Whale Rating: 2

Based on Jeremy Winn's study, diameter could affect the severity of entanglements. Testing displayed that rope cuts deeper into whale tissue as the diameter decreases (Winn et al., 2008, p. 340).

Total Weight: 4

Specific Gravity

This consideration encompasses whether an alternative will sink or float when placed in the water column.

Lobstermen Rating: 2

For an offshore application, regulations require that the top 1/3 of a vertical line be sinking. Therefore, the specific gravity of the rope would have to be greater than one in order to be in compliance with this regulation.

Whale Rating: 0

Vertical lines still would be in the water column despite the specific gravity of the rope.

Total Weight: 2

UV Resistance

This consideration indicates how well an alternative would withstand exposure to UV light.

Lobstermen Rating: 1

Only two lobstermen mentioned UV resistance as an important factor when choosing a rope. If an alternative is not UV resistant, a lobsterman may still use it. However, a lack of UV resistance would decrease the lifespan of the rope if the lobsterman did not store the rope properly.

Whale Rating: 0

North Atlantic right whales would become entangled in ropes regardless of UV resistance.

Total Weight: 1

5.1.1 Summary of Weighting the Considerations

A summary of the considerations and their respective weights can be seen in Table 12.

Table 12: Summary of Considerations and their Weights

Considerations	**Weighting**		
	Lobstermen	Right Whales	**Total**
Ability to be readily produced for the lobster fishing industry	1	1	2
Ability to be used in muddy bottoms	2	1	3
Ability to be used in rocky bottoms	2	1	3
Ability to coil	2	0	2
Ability to handle when wet	1	0	1
Ability to resist wear in hauler	2	0	2
Ability to splice the rope	1	1	2
Abrasiveness	2	2	4
1,500 pound Breaking Strength	2	2	4
Cost compared to current ropes	2	0	2
Degradation of breaking strength	2	1	3
Diameter	2	2	4
Specific Gravity	2	0	2
UV resistance	1	0	1

5.2 Scoring the Alternatives

As described in our Methodology Chapter, alternatives were scored based on how well they met our considerations. The meanings of each score can be seen in Table 13.

Table 13: Significance of Scores Assigned to Alternatives

Score	Significance of Score
3	Exceeds
2	Meets
1	Does Not Meet

Here, we describe our reasoning for assigning the scores that we did.

Polysteel

We assessed a rope currently used in the vertical lines of lobster traps on our multivariable assessment tool to have a baseline to compare the alternatives to. Although we know that Polysteel is contributing to entanglements of North Atlantic right whales, it received a total score of 73. Since this is a rope already being used in lobster fishing, we were able score this rope on all but one consideration. As a result, Polysteel has a low uncertainty rating. The assessment of Polysteel can be seen in Table 14.

Table 14: Assessment of Polysteel

Considerations	Scores for Current Rope (Polysteel)	Explanations of Scores
Ability to be readily produced for the lobster fishing industry	3	This rope is currently used in the lobster fishing industry; therefore, we gave it a score of 3 since it exceeds the consideration.
Ability to be used in muddy bottoms	3	This rope is currently used to fish in muddy bottom areas; therefore, we assigned a score of 3 since this rope could continue to be fished in these areas.
Ability to be used in rocky bottoms	3	Since this rope is currently used to fish in rocky bottom areas and could continue to be fished in these areas, we gave it a score of 3.
Ability to coil	3	We assigned a score of 3 for this rope's ability to coil because in our interviews with lobstermen they expressed that it coiled well.
Ability to handle when wet	X	We were unable to assess the rope on this consideration because the lobstermen we interviewed did not state its ability to handle when wet and we could not assess this on our own.
Ability to resist wear in hauler	2	The lobstermen we interviewed who use Polysteel expressed concerns about the rope's durability since the rope becomes worn after repeated use in the hauler. This information led us to give the rope a score of 2 for this consideration.

Considerations	Scores for Current Rope (Polysteel)	Explanations of Scores
1,500 pound Breaking Strength	1	We assigned a score of 1 for this consideration because 3/8 inch diameter of Polysteel has a breaking strength of 3,700 pounds.
Cost compared to current ropes	2	Polysteel is one of the current ropes used. Therefore, we gave the rope a score of 2 since the cost would remain comparable to what it is now.
Degradation of breaking strength	1	Through the analysis of entanglement case studies, breaking strengths of rope retrieved from entanglement after use are significantly lower than advertised breaking strength. Lobstermen also spoke about the way their rope weakens over time. For these reasons, we gave this rope a score of 1 for this consideration.
Diameter	2	This rope can be produced in a 3/8 inch diameter and therefore we assigned a score of 2 for this consideration.
Specific Gravity	2	Since the specific gravity of Polysteel is 0.91, we gave the rope a score of 2 for this consideration.
UV resistance	2	Polysteel has the ability to resist wear from UV light but the lobstermen we interviewed were dissatisfied with its ability. Therefore, we assigned a score of 2 for this consideration.
Total Score (Uncertainty Rating)	73 (Assessed on 13/14 considerations) Low Uncertainty Rating	

Shape Memory Alloys

Smart Memory Alloys received a total score of 30. This low score is partially attributed to low scoring of some considerations. For example, the alloys only received a score of “1” in regards to being able to be readily produced for the lobster fishing industry because this material has never been attempted to be used in existing ropes. SMAs received scores for six considerations which resulted in a moderate uncertainty rating. For example, the SMAs could not be scored on abrasiveness because there is no data on this. Although this material received a low total score, it did receive a score of “3” for its ability to coil since the material could be programmed to coil when removed from the ocean water. If a prototype could be developed using this material, then it could be assessed on more considerations, giving it a lower uncertainty rating. The assessment of shape memory alloys can be seen in Table 15.

Table 15: Assessment of Shape Memory Alloys

Considerations	Scores for Shape Memory Alloy (SMAs)	Explanations of Scores
Ability to be readily produced for the lobster fishing industry	1	We assigned this material a score of 1 because a rope has yet to be produced out of shape memory alloys.
Ability to be used in muddy bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Ability to be used in rocky bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Ability to coil	3	The main logic behind the use of SMAs is when the rope is taken out of the ocean water, it will automatically coil. Therefore, we assigned it a score of 3 for this consideration.
Ability to handle when wet	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Ability to resist wear in hauler	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Ability to splice the rope	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Abrasiveness	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
1,500 pound Breaking Strength	2	This material would be added to a rope with a 1,500 pound breaking strength. Therefore, we assigned a score of 2 for this consideration since the consideration is met.
Cost compared to current ropes	1	The cost of a rope with this material would add additional costs to rope because SMAs are still in the developmental process.
Degradation of breaking strength	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Diameter	2	This material would be added to a rope. Therefore, the rope could have a diameter comparable to an existing rope causing us to give this material a score of 2 for this consideration.

Considerations	Scores for Shape Memory Alloy (SMAs)	Explanations of Scores
Specific Gravity	2	A rope with this material would retain a specific gravity of greater than one since shape memory alloys are metals. For this reason, we assigned a score of 2 for meeting this consideration.
UV resistance	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Total Score (Uncertainty Rating)	30 (Assessed on 6/14 considerations) Moderate Uncertainty Rating	

<u>Shape Memory Polymers</u>

Shape memory polymers received a total score of 28. This low total score is a result of limited knowledge about this material. We could only score shape memory polymers on five out of the fourteen considerations, giving it a high uncertainty rating. For example, we could not determine its ability to splice since actual prototypes do not exist. We gave shape memory polymers a score of "2" for its ability to be produced. Although this alternative has the capability to be made into a rope, a rope with shape memory polymers does not currently exist. Furthermore, we assigned a score of "3" for shape memory polymers' ability to coil. The most attractive feature of shape memory polymers is that the material can be programmed to coil and uncoil based on the temperatures it is exposed to. The assessment of shape memory polymers can be seen in Table 16.

Table 16: Assessment of Shape Memory Polymers

Considerations	Scores for Shape Memory Polymer (SMPs)	Explanations of Scores
Ability to be readily produced for the lobster fishing industry	2	From our research, SMPs have the ability to be produced as a rope. However, a rope of SMPs has yet to be produced so we assigned a score of 2 for this consideration.
Ability to be used in muddy bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Ability to be used in rocky bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.

Considerations	Scores for Shape Memory Polymer (SMPs)	Explanations of Scores
Ability to coil	3	The main logic behind the use of SMPs is when the rope is taken out of the ocean water, it will automatically coil. Therefore, we assigned it a score of 3 for this consideration.
Ability to handle when wet	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Ability to resist wear in hauler	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Ability to splice the rope	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Abrasiveness	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
1,500 pound Breaking Strength	2	This material would be added to a rope with a 1,500 pound breaking strength. Therefore, we assigned a score of 2 for this consideration since the consideration is met.
Cost compared to current ropes	1	The cost of a rope with this material would add additional costs to rope because SMPs are still in the developmental process.
Degradation of breaking strength	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Diameter	2	This material would be added to a rope. Therefore, the rope could have a diameter comparable to an existing rope causing us to give this material a score of 2 for this consideration.
Specific Gravity	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
UV resistance	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the material's ability.
Total Score (Uncertainty Rating)	28 (Assessed on 5/14 considerations) High Uncertainty Rating	

Maxijacket Urethane Coating

Maxijacket Urethane Coating received a total score of 71. We assigned the coating a score of “3” fishing in rocky bottom and ability to be produced which contributed to its high score. This coating also received a “2” in diameter since the coating would not produce a noticeable increase in diameter of any rope it is applied to. Therefore, the rope would remain true to its initial diameter. The manufacturer also advertises this rope as resistant to snagging which would increases its feasibility for fishing in areas where rocks are present on the ocean floor. This resistance would increase the durability and lifespan of the rope. Maxijacket Urethane coating is also already produced for ropes in the marine industry; therefore, the implementation time into the lobster fishing industry may be small. Maxijacket Urethane coating scored well in comparison to the other alternatives in part because Maxijacket Urethane coating received scores on eleven out of fourteen considerations which provided it with a low uncertainty rating. The assessment of Maxijacket Urethane coating can be seen in Table 17.

Table 17: Assessment of Maxijacket Urethane Coating

Considerations	**Scores for Maxijacket Urethane Coating**	**Explanations of Scores**
Ability to be readily produced for the lobster fishing industry	3	This coating is already used on rope in other marine industries. Therefore, we assigned a score of 3 because a rope with this coating is already available.
Ability to be used in muddy bottoms	3	According to the manufacturer, this coating is abrasion and snag resistant. Therefore, we do not foresee difficulty in fishing in muddy bottoms and gave a score of 3 for this consideration.
Ability to be used in rocky bottoms	3	Since this coating reduces the risk of rope snagging on rocks, we assigned a score of 3 for this coating's ability to fish in rocky bottoms.
Ability to coil	2	According to the manufacturer, applying this coating does not cause a difference in flexibility compared to the flexibility of the rope the coating is applied to. Since this coating meets the consideration, we assigned a score of 2.
Ability to handle when wet	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to resist wear in hauler	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.

Considerations	Scores for Maxijacket Urethane Coating	Explanations of Scores
Ability to splice the rope	2	According to the manufacturer, the addition of this coating to a rope has no effect on the ability to splice the rope. Therefore, we assigned a score of 2 for meeting this consideration.
Abrasiveness	3	This coating creates a low abrasive surface on the rope it is applied to. Therefore, we gave a score of 3 for this consideration.
1,500 pound Breaking Strength	2	This coating would be applied to a rope with a 1,500 pound breaking strength. Since this coating would meet the consideration, we assigned a score of 2.
Cost compared to current ropes	2	This coating would not cause a significant additional cost to the current rope. Therefore, we gave a score of 2 for this consideration.
Degradation of breaking strength	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Diameter	2	This coating would not significantly affect the diameter of the rope it is applied to. Therefore, we assigned a score of 2 for meeting this consideration.
Specific Gravity	2	According to the manufacturer, this coating would not affect the specific gravity of the rope it is applied to. As a result, we assigned a score of 2 for this consideration.
UV resistance	3	According to the manufacturer, applying this coating to a rope would add UV resistance to the rope. Therefore, we gave a score of 3 for this consideration.
Total Score (Uncertainty Rating)	71 (Assessed on 11/14 considerations) Low Uncertainty Rating	

<u>TrueKote CS-100</u>

TrueKote CS-100 received a total score of 42. We assigned this alternative a score of “1” for cost because the coating would require an additional cost of $567.00 for one 1,200 foot coil of rope to the purchase of a 1,500 pound breaking strength rope. We assigned TrueKote CS-100 a score of “3” in terms of abrasiveness because this alternative could provide a smooth outer coating to the rope. We also scored TrueKote CS-100 a “2” for diameter because the cure time would allow the diameter to meet any desired specifications. This alternative only received a score for seven considerations giving it a moderate uncertainty rating. The assessment of TrueKote CS-100 can be seen in Table 18.

Table 18: Assessment of TrueKote CS-100

Considerations	Scores for TrueKote CS-100	Explanations of Scores
Ability to be readily produced for the lobster fishing industry	3	This coating is already produced and could be applied to the current lobster fishing rope. As a result, we assigned a score of 3 for this consideration.
Ability to be used in muddy bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to be used in rocky bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to coil	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to handle when wet	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to resist wear in hauler	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to splice the rope	1	According to the manufacturer, this rope cannot be spliced. Therefore, we assigned a score of 1 for not meeting this consideration.
Abrasiveness	3	According to the manufacturer, this coating would provide a low abrasive surface to the rope. As a result, we gave a score of 3 for this consideration.
1,500 pound Breaking Strength	2	This coating would be applied to a rope with a 1,500 pound breaking strength. Since this coating would meet the consideration, we assigned a score of 2.
Cost compared to current ropes	1	This coating would cause significant additional costs to the current rope used. Therefore, we gave a score for 1 for this consideration.
Degradation of breaking strength	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Diameter	2	Since this coating can be repeatedly applied to a rope until a desired diameter is achieved, we assigned a score of 2 for meeting the consideration.

Considerations	Scores for TrueKote CS-100	Explanations of Scores
Specific Gravity	2	Since this coating has a specific gravity greater than one, we gave a score of 2 for this consideration.
UV resistance	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Total Score (Uncertainty Rating)	42 (Assessed on 7/14 considerations) Moderate Uncertainty Rating	

Truecoat CS-252

Truecoat CS-252 received a total score of 40. We scored this alternative on seven out of our fourteen considerations, causing Truecoat CS-252 to have a moderate uncertainty rating. We scored this alternative's diameter a "2" and abrasiveness a "3". Since Truecoat CS-252 is a coating, multiple applications can be made onto a rope in order to customize the diameter. This alternative will also create a smooth outer surface on the rope which will decrease its abrasiveness. However, we assigned Truecoat CS-252 a score of "1" for the cost compared to the current rope consideration. This coating would require an additional $557.00 to the current rope cost. The assessment of Truecoat CS-252 can be seen in Table 19.

Table 19: Assessment of Truecoat CS-252

Considerations	Scores for Truecoat CS-252	Explanations of Scores
Ability to be readily produced for the lobster fishing industry	2	This rope is currently produced with established manufacturing processes, however the manufacturer expressed concern with applying this coating to long strands of rope
Ability to be used in muddy bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to be used in rocky bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to coil	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.

Considerations	Scores for Truecoat CS-252	Explanations of Scores
Ability to handle when wet	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to resist wear in hauler	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Ability to splice the rope	1	According to the manufacturer, this rope cannot be spliced. Therefore, we assigned a score of 1 for not meeting this consideration.
Abrasiveness	3	According to the manufacturer, this coating would provide a low abrasive surface to the rope. As a result, we gave a score of 3 for this consideration.
1,500 pound Breaking Strength	2	This coating would be applied to a rope with a 1,500 pound breaking strength. Since this coating would meet the consideration, we assigned a score of 2.
Cost compared to current ropes	1	This coating would cause significant additional costs to the current rope used. Therefore, we gave a score for 1 for this consideration.
Degradation of breaking strength	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Diameter	2	Since this coating can be repeatedly applied to a rope until a desired diameter is achieved, we assigned a score of 2 for meeting the consideration.
Specific Gravity	2	This coating would not affect the specific gravity of the rope that it is applied to. Since it meets this consideration, we assigned a score of 2.
UV resistance	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the coating's ability.
Total Score (Uncertainty Rating)	40 (Assessed on 7/14 considerations) Moderate Uncertainty Rating	

<u>Novabraid Duraflex Lead Core</u>

The Novabraid Duraflex Lead Core rope received a total score of 44. We scored this alternative on eight out of our fourteen considerations; therefore, the Novabraid Duraflex Lead Core has a moderate uncertainty rating. We did not give this alternative a score for cost since this data is not available. We also assigned this rope a “1” for its ability to splice because its lead core would not allow splicing. Furthermore, we gave this alternative a score of “3” for its ability to be produced. These scores are a result of the fact that this alternative already exists as a rope. The assessment of Duraflex Lead Core rope can be seen in Table 20.

Table 20: Assessment of Novabraid Duraflex Lead Core Rope

Considerations	Scores for Novabraid Duraflex Lead Core	Explanations of Scores
Ability to be readily produced for the lobster fishing industry	3	This rope is currently produced and marketed towards the gillnet fishing industry. Therefore, the rope could be easily ready for use in the lobster fishing industry. For this reason, we assigned a score of 3 for this consideration.
Ability to be used in muddy bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Ability to be used in rocky bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Ability to coil	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Ability to handle when wet	2	Since this rope has a braided polyester and polypropylene sleeve, this rope would have a similar handling ability as current ropes used in the lobster fishing industry. For this reason, we assigned a score of 2 for this consideration.
Ability to resist wear in hauler	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Ability to splice the rope	1	Since this rope is made with lead and therefore is not able to be spliced, we gave it a score of 1 for not meeting the consideration.
Abrasiveness	3	According to the manufacturer, this rope is not abrasive. Therefore, we assigned a score of 3 for this consideration.
1,500 pound Breaking Strength	2	1,500 pounds falls within this rope's range of breaking strength. As a result of meeting this consideration, we gave a score of 2.
Cost compared to current ropes	X	We were unable to assign a score for this consideration because we could not acquire this data.

Considerations	Scores for Novabraid Duraflex Lead Core	Explanations of Scores
Degradation of breaking strength	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Diameter	2	This rope can be manufactured with a range of diameters. Therefore, we assigned a score of 2 for meeting this consideration.
Specific Gravity	2	Since this rope is made with lead, which has a specific gravity greater than one, the rope's specific gravity would be greater than one. For this reason, we gave a score of 2 for meeting this consideration.
UV resistance	2	According to the manufacturer, the sleeve of this rope is UV resistant. Therefore, we assigned a score of 2 for meeting this consideration.
Total Score (Uncertainty Rating)	44 (Assessed on 8/14 considerations) Moderate Uncertainty Rating	

Novabraid Norpacific Gillnet Corkline High Tenacity

Based on the scores we assigned, the Novabraid Norpacific Gillnet Corkline High Tenacity rope received a total score of 42. We had sufficient knowledge of this rope to assess it on seven of our fourteen considerations; therefore, the Novabraid Norpacific Gillnet Corkline High Tenacity rope has a moderate uncertainty rating. Furthermore, we gave the Novabraid Norpacific Gillnet Corkline High Tenacity rope a score of “2” for specific gravity because its specific gravity is greater than one. In addition, we assigned a score of “2” for its UV resistance because it is comparable to that of the current ropes used in the lobster fishing industry. The assessment of Norpacific Gillnet Corkline High Tenacity rope can be seen in Table 21.

Table 21: Assessment of Novabraid Norpacific Gillnet Corkline High Tenacity Rope

Considerations	Scores for Novabraid Norpacific Gillnet Corkline High Tenacity	Explanations of Scores
Ability to be readily produced for the lobster fishing industry	3	This rope is currently produced and marketed towards the gillnet fishing industry. Therefore, the rope could be easily ready for use in the lobster fishing industry. For this reason, we assigned a score of 3 for this consideration.
Ability to be used in muddy bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Ability to be used in rocky bottoms	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Ability to coil	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Ability to handle when wet	2	Since this rope has a braided polyester and polypropylene sleeve, this rope would have a similar handling ability as current ropes used in the lobster fishing industry. For this reason, we assigned a score of 2 for this consideration.
Ability to resist wear in hauler	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Ability to splice the rope	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Abrasiveness	3	According to the manufacturer, this rope is not abrasive. Therefore, we assigned a score of 3 for this consideration.
1,500 pound Breaking Strength	2	1,500 pounds falls within this rope's range of breaking strength. As a result of meeting this consideration, we gave a score of 2.
Cost compared to current ropes	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.
Degradation of breaking strength	X	We were unable to assign a score for this consideration because we could not perform the tests needed in order to determine the rope's ability.

Considerations	Scores for Novabraid Norpacific Gillnet Corkline High Tenacity	Explanations of Scores
Diameter	2	This rope can be manufactured with a range of diameters. Therefore, we assigned a score of 2 for meeting this consideration.
Specific Gravity	2	Since the specific gravity of this rope is greater than one, we gave a score of 2 for meeting this consideration.
UV resistance	2	According to the manufacturer, the sleeve on this rope does not degrade when exposed to UV light. Therefore, we assigned a score of 2 for meeting this consideration.
Total Score (Uncertainty Rating)	42 (Assessed on 7/14 considerations) Moderate Uncertainty Rating	

In all of the previous tables, the X's represent areas in which we did not have enough knowledge to accurately assess an alternative. At this point, a low score is not indicative of a less optimal solution. A solution would only be deemed less optimal when it received a low score in conjunction with a low uncertainty rating.

When assessing alternatives on certain characteristics, we believed that the importance of some characteristics was not reflected in their weight. For example, specific gravity was only assigned a weight of 2. However, for an alternative to be legally implemented into the lobster fishing industry, it must have a specific gravity of greater than 1.00. Therefore, if an alternative received a score of "1" in this category, *it could not be considered a viable alternative, regardless of its total score.* Therefore, we determined specific gravity to be a negating factor, or a consideration whose importance is not accurately reflected in its overall weight. Through a more thorough weighting process or after in-field testing, more negating factors may be identified. This limitation of our multivariable assessment tool could be overcome in the future if negating factors are used to pre-screen alternatives prior to assessment.

Through our assessment of alternatives, we discovered that our multivariable assessment tool is useful in the assessment process. It provides specific considerations of alternatives that must be determined as well as the relative importance of those considerations. It ensures that the effectiveness of a potential alternative is assessed from more than one perspective.

6.0 Conclusions and Recommendations

The goal of this project was to develop and test a framework with which to assess the characteristics of an alternative 1,500 pound breaking strength rope that would be safer for North Atlantic right whales and effective for lobster fishing. In this chapter, we present our recommendations for the next steps in pursuing 1,500 pound breaking strength ropes. These recommendations can not only benefit the pursuit of 1,500 pound breaking strength rope alternatives specifically, but any future alternatives researchers pursue. These recommendations are a result of the information presented in both the Findings and Discussion Chapters. This chapter is separated into three subsections:

6.1 Recommendations for Future Plans to Assess Alternative Ropes
6.2 Future WPI Projects
6.3 Final Remarks

6.1 Recommendations for Future Plans to Assess Alternative Ropes

Recommendation #1: We recommend future proposed rope alternatives be assessed using our multivariable assessment tool through cooperation between all relevant perspectives.

As stated in Finding 12, our multivariable assessment tool provides a valuable framework that encompasses a variety of perspectives that are relevant to the problem presented by entanglement of North Atlantic right whales. Incorporation of the various perspectives is essential so all parties feel as though their perspectives are considered in potential solutions. This approach makes solutions more likely to benefit all of those involved. A lobsterman stated in one of our interviews that “disconnect between the industry” and those proposing gear modifications is a significant problem. To resolve this problem, a system should be developed by relevant stakeholders, including lobstermen and whale researchers to determine the effectiveness of alternatives. This system would include a testing phase as well as a reassessment phase, using the multivariable assessment tool. A multivariable assessment tool, exemplified by the one we produced, could be effective in determining the most optimal solution. Therefore, we strongly recommend future alternatives be assessed using the process we have developed in this project.

Recommendation #2: We recommend different vertical line rope alternatives be pursued in fishing areas with different conditions.

An overwhelming consensus amongst lobstermen and researchers we interviewed was that different fishing locations have drastically different needs, especially when differentiating between inshore and offshore fishing or muddy and rocky bottom areas. We strongly recommend that future rope alternatives have properties tailored to the area they will be implemented in. A single vertical line rope alternative may not be successful across the entire lobster fishing industry. Therefore, researchers and lobstermen alike should identify criteria alternatives rope must meet in different regions.

Recommendation #3: We recommend not pursuing a specific alternative until it has been thoroughly researched.

As stated in our Discussion Chapter, a low total score on our multivariable assessment tool does not indicate a less optimal solution. In our assessment, low total scores revealed a lack of information, rather than poor potential performance. An alternative's potential could only be accurately assessed once it could be scored on the majority of considerations. The uncertainty rating reflects how many considerations a particular alternative could be assessed on. More information about an alternative would result in a lower uncertainty rating and a more robust scoring. Alternatives with high total scores and low uncertainty scores may be the most promising solutions to pursue. Therefore, we recommend only alternatives with low uncertainty ratings and high scores be subjected to further in-field testing or implementation to increase the likelihood that changes will be successful.

Recommendation #4: We recommend that the next step in researching shape memory materials is determining whether the technology can be manufactured into a viable rope*.*

As stated in Finding 9, shape memory materials have potential as lobster fishing rope alternatives. To test the characteristics of a shape memory material alternative, the technology first needs to be manufactured into a workable rope. After a functional rope has been manufactured from shape memory materials, the rate in which the rope can coil and whether this coiling action poses a safety threat onboard a vessel will need to be evaluated by lobstermen. If the rope is deemed safe, the New England Aquarium research team or the Consortium of Wildlife Bycatch Reduction could distribute the rope along the coast of Maine and Massachusetts to lobstermen. To further assess the effectiveness, the lobstermen could then score the shape memory materials with our multivariable assessment tool.

Recommendation #5: We recommend experimental testing with rope coatings.

As stated in Finding 10, applying a synthetic coating to a vertical line of a lobster trap with a breaking strength of 1,500 pounds could make the rope line more appealing to lobstermen and less harmful to North Atlantic right whales. The coatings were given low or moderate uncertainty ratings and therefore, could be tested sooner than other alternatives since little additional research would be required. We recommend lower breaking strength ropes be coated with the three coatings discussed in Finding 10 and given to lobstermen in Maine and Massachusetts to test under fishing conditions. The lobstermen would then be able to reassess the rope on our multivariable assessment tool and provide a more informed total score. If the new score reflects an increase in feasibility compared to current rope and still satisfies the considerations that provide a safer alternative for North Atlantic right whales, large scale implementation could then be possible.

Recommendation #6: We recommend giving samples of the existing ropes we explored to lobstermen to determine the feasibility of implementing them in the vertical lines of lobster traps.

As stated in Finding 11, there are existing ropes that could serve as alternatives for lower breaking strength rope in the lobster fishing industry. However, there are insufficient data regarding the feasibility of these existing ropes in the lobster fishing industry. Even though these ropes are currently used in marine environments, they have not been tested under the rigorous conditions lobstermen put their gear through. The best way to determine how these ropes will perform is to purchase samples to distribute amongst lobstermen along the coast of Maine and Massachusetts. These ropes need to be tested on the considerations that we could not assess on our multivariable assessment tool.

Recommendation #7: We recommend researchers use the right whale entanglement simulator to further determine how the breaking strength of vertical lines of lobster traps affects the safety of North Atlantic right whales.

As stated in Finding 1, the breaking strength of vertical line rope is an important factor when considering the safety of North Atlantic right whales. More research is necessary to explore the implications of a 1,500 pound breaking strength rope on North Atlantic right whales. Researchers recognize that the success of any given technique can only be determined through implementation and then analysis of subsequent entanglements over time. We recommend that the right whale entanglement simulator, as mentioned in section 2.7, be used. The project, which is currently under development, would allow a computer simulation to test the interactions between vertical line rope and North Atlantic right whales. If the rope can be designed to have a 1,500 pound breaking strength, evidence of the ideal breaking strength could be determined in a non-harmful way to the whales.

Recommendation #8: We recommend conducting further research to determine the relationship between rope diameter and extent of whale injury resulting from entanglement.

As stated in Finding 2, the diameter of the vertical line rope is inversely proportional to the extent of North Atlantic right whale injury. After reviewing Woodward and Winn's right whale tissue studies, we determined that ropes with a thicker diameter should be tested against tissue samples. In the studies, the largest diameter used was 3/8 inch; however, after interviewing lobstermen, many actually use ropes larger than 3/8 inch which is discussed in Finding 7 (Winn et al., 2008, p. 330). The evidence could potentially provide a range of diameters that would be significantly less harmful to North Atlantic right whales.

6.2 Proposed Future WPI Projects

Recommendation #9: We recommend a project dedicated to the implementation of a new gear marking system.

From our interviews with right whale researchers, we concluded determining the origin of gear retrieved off of North Atlantic right whales is extremely difficult. Currently, there is a system that registers and marks buoys so that lobstermen recognize which gear is theirs. However, when gear is retrieved off of North Atlantic right whales, the buoys or traps are not necessarily attached and gear cannot be identified. As a result of a poor gear marking system, the entanglement data available to researchers is limited. Therefore, we strongly recommend that future research investigates how to implement a gear marking system that would allow researchers to collect more information regarding gear involved in entanglements. If researchers can confirm that North Atlantic right whale entanglements occur in specific areas, future modifications could be implemented in only those areas as opposed to the entire industry. The outcome of the project will provide valuable information on how to best approach a gear marking system.

Recommendation #10: We recommend a project dedicated to raising lobstermen awareness of North Atlantic right whales.

Through our interviews with lobstermen, we concluded that some lobstermen do not understand the overlap of that the North Atlantic right whales and their gear. An educational program could help educate lobstermen about North Atlantic right whales and their interaction with the lobster fishing industry. An educational program could consist of a combination of brochures, YouTube videos, social media campaigns, and presentations.

Some lobstermen we interviewed displayed particular interest in the species and wanted to learn more about North Atlantic right whales. The positive reactions of these lobstermen indicate an educational program may be beneficial to and welcomed by lobstermen. Specific details that could be provided about the whales include basic information such as their appearance, food source, and general location throughout the year. Lobstermen should understand how whales can get entangled in lobster traps. The right whale entanglement simulator aims to explain how entanglements occur and would make a great visual representation. Bringing lobstermen into this discussion would ensure that they understand the ramifications of the overlap as well as incorporate their perspective in actions taken to reduce entanglements. Educating lobstermen may change their perspectives and foster more cooperation between lobstermen and researchers. This cooperation is essential in the development of a successful alternative.

6.3 Final Remarks

This project developed a framework with which to assess the potential for 1,500 pound breaking strength alternative ropes for use in the lobster fishing industry that would be safer for North Atlantic right whales. With 82% of the North Atlantic right whale population affected by entanglements, a reduction of entanglements is critical. Alternative ropes would be used in the vertical line rope of lobster traps, which are the main identifiable source of North Atlantic right whale entanglements. As part of our project, we developed a multivariable assessment tool with the purpose of providing a method to assess rope alternatives. Our multivariable assessment tool does more than simply assess the alternatives we determined; it provides a framework to involve all stakeholders in this incredibly complex problem. Cooperation between researchers, manufacturers, and lobstermen is essential to save the remaining individuals in the North Atlantic right whale population. This tool provides a method for collaborative and constructive cooperation.

We then applied and tested this tool. We determined the considerations necessary to increase the safety of North Atlantic right whales through analysis of entanglement case studies and interviews with whale researchers. To incorporate the perspectives of lobstermen, we performed interviews with ten Maine lobstermen and supported those interviews with a stress strain test on a sample of used rope. We investigated innovative materials, coatings, and existing ropes that could be given to the New England Aquarium to develop further. We also provided the New England Aquarium with a detailed analysis of all alternatives assessed on this tool. In addition to data sheets about the alternatives we assessed, we provided our multivariable assessment tool and protocol for using it. Our findings and multivariable assessment tool could be useful long past the scope of this project. We hope that our multivariable assessment tool will aid researchers in developing gear modifications that have a lasting, positive impact on the North Atlantic right whale species as a whole.

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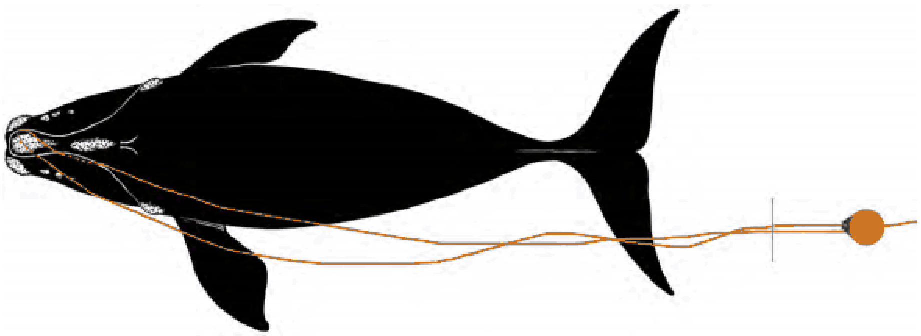
Appendix A: Example of an Entanglement Case Study

Species	Right Whale	Whale ID	Eg #1427

Date first observed entangled (date seen prior without gear)	12 Jul 2002 (08 May 2002)		
Sex	Male	Birth year	1984
Age at entanglement	18		

	PCCS	NMFS	GEAR ID
Case study ID	WR-2002-14	E17-02	J071202
Gear sample collected?	Yes	Gear type	Unknown



Reproductive prior to entanglement detection?					
Reproductive after entanglement detection?					
Entanglement severity	Moderate				
Wound severity	Mouth	Head/ Rostrum	Flippers	Body	Flukes
	Medium	Medium	Unknown	Low	Medium
Duration of time carrying gear	Minimum 9 days, maximum 485 days				
Disentangled?	No -Gear shed				
Status	Alive - Last sighted in 2009				
Number of prior entanglement interactions	4				

Entanglement configuration	Line caught in mouthline, far forward on the head and leading to ~150ft of trailing line and balloon buoy.
Anchoring point(s)	Mouthline
Gear configuration confidence	High
Remaining questions	Flippers do not appear to have been involved but not possible to verify.
Comments	Whale was tagged for possible disentanglement but this was removed by recreational boater; whale seen months later gear-free.

Polymer type		Polysteel
Gear component		Vertical line
Rope diameter (inches)		5/8 (0.630)
Breaking strength (lbs)	Tested	7 241
	New	9 000

Knowlton, A.R., J. Robbins, S. Landry, H. McKenna, T. Werner. 2012. Case Studies in Entanglements of Right Whales and Humpback Whales. In partial fulfillment of a final report by the Consortium for Wildlife Bycatch Reduction, NOAA Award # NA09NMF4520413

Appendix B: Analysis of Entanglement Case Studies

EG#	Age at Entanglement	Disentangled (Shed/By Team/remained entangled)	Duration of Entanglement (Min - Max)	Severity of Entanglement
1971	8	Yes - By Team	22- 346 days	Moderate
2212-2	6	Yes Partially - By Team	1 - 24 days	Minor
2220	5+	No	85 - 115 days	Severe
2427	7	Yes - By Team	1 - 211 days	Severe
3294	7+	No	10-291	Moderate
2710	2	Yes	55-389	Moderate
3107	1	Yes, by team.	57-266 days	Severe
3120	1	Peduncle wrap by team, rest shed by whale	433-808 days	Moderate
3314	2	Yes, by team.	9-96	Moderate
3346	1	Yes, by team (partial)	2569-2615	Severe
3392	1+	Yes	Unknown	Moderate
3821	1	Yes	1-76	Minor

EG#	Status/Cause of Death	Gear Type	Gear Component	Diameter
1971	Alive	Lobster Offshore	Vertical	1/2
			Vertical	9/16
			Surface System	9/16
2212-2	Presumed Dead	Lobster	Vertical	5/16
				3/8
2220	Dead in same year of first observation	Lobster	Unknown	3/8
2427	Alive	Lobster Offshore	Surface System	9/16
				5/8
3294	Alive	Lobster	Unknown	5/16
2710	Alive	Lobster	Unknown	1/2
3107	Dead, 1 month post entanglement	Lobster inshore	Vertical	3/8
3120	Alive	Lobster inshore	Unknown	5/16
				3/8
				3/8
3314	Alive	Lobster	Vertical	7/16
				3/8
				3/8
3346	Alive	Lobster	Vertical	3/8
3392	Alive	Lobster	Vertical	3/8
3821	Alive	Lobster	Vertical	3/8

EG#	Polymer Type	Advertised Breaking Strength (lbs)	Tested Breaking Strength (lbs)	Rope Condition
1971	PP/PET	4500	3648	Moderate
	PP/PE	5000	1580	Poor
	PP	4590	4381	Moderate
2212-2	PP	1700	1615	Moderate
	PP/PET	2600	1692	Good
2220	PP	2430	1442	Moderate
2427	PP/PET	5000	2029	Fair
	Polysteel	9000	4339	Fair
3294	PP	1700	1670	Good
2710	PP	3780	3339	Good **Canadian
3107	Polysteel/PET	3400	2254	Moderate
3120	PP	1700	1726	Fair
	PP	2430	1700	Moderate
	Polypro/PET	2600	1580	Poor
3314	Polysteel	4100	2431	Moderate
	Polysteel	3400	2592	Moderate
	PP/PET/Lead	2000	2000	Good
3346	Polypro/PET	2600	1597	Unknown
3392	PP/PET	2600	1717	Excellent
3821	PP/PET	2600	2140	Moderate

Appendix C: Researcher Interview Summary

Allison Henry: NOAA employee, Woods Hole, MA

- Collects data regarding whale deaths and serious injuries, reviews necropsies
- Focuses mostly on ropes that are most likely to kill a whale
- Described the potential biological reduction, or number of whales that can die as a result of non-natural causes each year and not have a negative impact on the population
    - 0.9 for NARW
- Most gear is not identified, flawed gear marking system
- Entanglements take approximately six months to kill a whale
- Offshore gear is most likely cause of entanglement
- One incident over gear attributed to a specific fishery has huge, lasting impacts on that fishery
- Fines for people who help report ship strikes and entanglements
- Flipper entanglement is most prevalent location on whale for entanglement, followed by peduncle and mouth

Scott Kraus, VP for Research at NEAq and Amy Knowlton, Research Scientist at NEAq

- 3 main categories of gear modification: ropeless, sensory capabilities of the whales, physical characteristics of ropes
- Ropeless
    - acoustic release technologies using transponders
    - industry and regulators would hate it
- Sensory
    - acoustic deterrents
    - illuminated rope
    - electronic ropes
    - colored ropes
- Physical Characteristics of Ropes
    - stiff ropes
    - weak ropes
- Lobstermen will be more willing to accept changes in gear when the gear solves their economic problems
- Convince highliners to change, that will drive the industry to change
- 1,500 pound breaking strength may not save calves
- Very little data about where whales pick up gear
    - Entanglements can happen anywhere gear is located
    - prevalence of entanglements about the mouths take researchers think offshore gear is more responsible than inshore gear

Appendix D: Interview Guide for Lobstermen

Operational Considerations:

- Do you fish doubles, singles, or trawls? or combination?
- What length of rope do you use per single, double, trawl?
- What characteristics do you consider important when you purchase rope for your vertical line?
    - durability? abrasion resistance? diameter? price? availability?
        - Which is most important? Which is least important?
- What ropes do you currently buy for your vertical lines?
    - Do you encounter any problems with this rope?
- What diameter of rope do you currently use?
- What diameter of rope would your hauler tolerate?
- How much do you typically spend on vertical lines in a year?
- How often do you replace your rope?
- What is the process every time you buy more rope?
- splicing?
- extra preparation steps?

Gear Loss:

- How much gear do you lose on average in a year?
    - What do you think the main cause is of your gear loss?
- How much new rope do you need to buy in a given year owing to gear loss?
- What is a typical replacement cost for that lost gear?
- How often do you retrieve gear that is not readily “haulable” because of breakage in vertical line?

Appendix E: Lobstermen Interview Summary

Interviewee Number	Zone	Inshore/Offshore	Diameter
1	C and D	Inshore	5/8 or 3/8
2	5 miles off Lubec 467 and 511 areas (Zone A)	Unknown	1/2 inch
3	Zone A	Offshore	7/16 inch; different at different depths, use thicker rope at bottom, smaller rope is almost half of the entire rope
4	C and D	Inshore	11/32 inch
5	Zone A	Inshore	7/16 to 1/2 inch
6	Zone F	Inshore	7/16 and 1/2
7	Zone A	Offshore	7/16 (float rope, trap to halfway up) and 3/8 or 11/32 (top rope)
8	Zone B	Both	7/16 (float rope), smaller on top 11/32 or 3/8 (sink rope)
9	Zone C	Offshore	10 fathoms of 5/16 diameter, 30 fathoms of 9/32 or 7/16, 15 fathoms 3/8 and 7/16 float rope
10	Unknown	Inshore	11/32 and 3/8 (sink: off buoy, float: connected to trap)

Interviewee Number	Zone	Inshore/Offshore	Diameter	Brand	Length	Important Characteristics
1	C and D	Inshore	5/8 or 3/8	Potward	Unknown	sinking
2	5 miles off Lubec 467 and 511 areas (Zone A)	Unknown	1/2 inch	Steel Liner and Float Rope (no brand)	Unknown	durability, abrasion resistance
3	Zone A	Offshore	7/16 inch; different at different depths, use thicker rope at bottom, smaller rope is almost half of the entire rope	Steel Liner or Esterpro	125 fathoms	safety, diameter
4	C and D	Inshore	11/32 inch	Polysteel currently (changes with year)	Unknown	durability, resists cutting, would prefer if it wore evenly
5	Zone A	Inshore	7/16 to 1/2 inch	Steel Liner Float and Polysteel	25 fathoms and 40 fathoms of sink rope	how it feeds into hauler, strong enough for anchors, hold up to big tides
6	Zone F	Inshore	7/16 and 1/2	Everson Sink (float rope on bottom)	Unknown	durability, abrasion resistance
7	Zone A	Offshore	7/16 (float rope, trap to halfway up) and 3/8 or 11/32 (top rope)	Not Specific	125 - 175 fathoms	durability, doesn't like soft rope
8	Zone B	Both	7/16 (float rope), smaller on top 11/32 or 3/8 (sink rope)	Top SuperTrawl, Floating Mainline, Seaside, Polysteel	90-110 fathoms in winter	handling qualities, how it comes out of hauler, strength, durability
9	Zone C	Offshore	10 fathoms of 5/16 diameter, 30 fathoms of 9/32 or 7/16, 15 fathoms 3/8 and 7/16 float rope	Super Pro (Waterville, Canada)	see Diameter	Unknown
10	Unknown	Inshore	11/32 and 3/8 (sink: off buoy, float: connected to trap)	Variety	20 - 50 feet	flexibility, coil-ability, ease of splicing, longevity in marine environment

Interviewee Number	Singles/Doubles/Trawls	Number of Traps	Cost of Vertical Lines
1	Doubles	50	1200ft cost = over $100
2	Trawl - 14 traps, 2 vertical lines	800	$15000/year
3	Trawl - 15 traps	700-800	30 - 40 coils/year
4	Doubles	owns 500, fishes 200	Unknown
5	Trawl - 10 traps, 2 vertical lines	Unknown	15 coils $100/coil
6	Trawl - 5-6 traps, 2 vertical lines	600	$12,000 replacement
7	Triples, 1 vertical line / Trawl - 12 traps, 2 VL with anchor later in season and further offshore	800	15-20 coils/ year $125/coil
8	Hancock County Rule: no trawls within 22 miles, 90% gear has 1 VL	Unknown	15-20 coils/year
9	Trawl - 5 traps, 2 VL increases during winter	800	$12,000/year
10	Doubles	Unknown	1 coil/3 years (spent $80 this year)

Interviewee Number	Lifespan of Vertical Line	Fishing Conditions
1	Unknown	Unknown
2	Unknown	Unknown
3	New rope with new traps, replaces 30-40% rope, 5-6 years	Unknown
4	2-3 years	Rocky bottom and mud close to 3 mile line
5	3 years	Unknown
6	3-5 years in muddy, 2 years in rocky	Mostly muddy bottom, 15% trap in rocky bottom
7	4-5 years	Mud in fall, rocky bottom as season progresses
8	10- 15 years (always replacing rope)	High tides in winter
9	Durability of rope used 10 years, endlines last 4-5 years	Muddy bottom, 50 fathoms deep
10	Only replaces rope when its frayed or cut into	Unknown

Interviewee Number	Gear Loss	Thoughts of Gear Loss	Cost of Gear Loss
1	8 traps this year	Boats	Unknown
2	100-200/year; 20 this year	Boats	$25,000-$30,000
3	Very little, sells old traps back; 20 traps this year, plan to recover	Unknown	Unknown
4	10% / year	Snaps off	Unknown
5	3-4 trawls/year	Boats, moved, gear on top	$3000/year
6	20 traps/ year	Bogged down, disappear	$12,000
7	20-40 traps/ year	Boats	4 lost traps = $500
8	10% / year	Boats, storms, cruise ships	$15, 000 including traps
9	30-40 traps/year	Boats	$4,000/year
10	12-14 traps/year, 6-7 buoys and vertical lines	Boats, deep water	Unknown

Interviewee Number	Thoughts of 1500lb Breaking Strength Rope
1	Unknown
2	Would break if traps got stuck
3	Could lead to more ghost gear, 3700lb sometimes breaks
4	Rope wears with time
5	Not interested, anything could shred it
6	Sees no problem with it, uses 1100lb, wouldn't work in rocky bottom
7	Wouldn't be long before strength deteriorated to 1000lb if you had to tie, splicing decreases the breaking strength, not good for rocky bottom
8	"We've dismissed it", major tides and major drags with buoys, "never seemed feasible at all", doesn't not seem strong enough for offshore, current gear snaps , sounds good on paper
9	Heard of it before, as long as same diameter it shouldn't be a problem
10	Current rope is 2800lb breaking, doesn't think it would be an issue with hauling doubles, doesn't want too thin of diameter, rope may get caught and force then may exceed 1500

Interviewee Number	Anchors Used?	Type of Lobsterman	Whales
1	wWeights to hold down float rope	Recreational	Unknown
2	Unknown	Unknown	Unknown
3	30-40 lbs	Commercial	Never seen an entangled whale, seen dead one with gear
4	No	Semi-retired	In 30 years, seen 3 whales
5	75 lb anchors on both vertical lines	Unknown	Unknown
6	Unknown	Unknown	Unknown
7	Later in season, further off shore	Unknown	Unknown
8	Unknown	Unknown	Unknown
9	Unknown	Unknown	Unknown
10	Unknown	Unknown	Unknown

Interviewee Number	Miscellaneous
1	Hauler: up to inch diameter
2	Weak links don't work
3	Lead core rope doesn't coil and go through hauler well; if you change the diameter you have to change hauler configurations; the smaller the diameter, lower force during tide; Canadians use float rope, float rope everywhere; weak links don't work
4	Hauler can ruin new rope; braided rope is too soft; smaller rope won't work in hauler, bigger rope would cause drag with buoy
5	Distinction between ropes is a problem; no problem with weak links
6	Has used Quint's lead rope
7	Unknown
8	Disconnect with industry is the problem, one size does not fit all for the industry
9	Uses nylon rope in top sinking rope, holds up well; rope rarely breaks during hauling
10	Unknown

Appendix F: Shape Memory Materials Summary Table

Rope Characteristics	Shape Memory Alloy	Shape Memory Polymer
Production State	Shape memory alloys are currently produced into the underwire in some women's bras (Stoeckel, 1991, p. 50).	The production state of this material is dependent on the type of plastic used. In some cases, the plastic used may already have the capabilities to be produced into a fiber while for other plastics a new process must be developed to extrude it into a fiber.
Ability to be used as a vertical line in the lobster industry	Shape memory alloys have not been applied to an existing rope yet, therefore its performance as a vertical line is unknown.	Many shape memory polymers have not been produced into a rope yet, therefore its performance as a vertical line is unknown.
Flexibility	Shape memory alloys have not been applied to an existing rope yet, however while in the austenite state this material will resist any bending action.	Many shape memory polymers have not been produced into a rope yet, however this material will resist any bending action while in the austenite state.
Interaction with water	Shape memory alloys have not been applied to an existing rope yet, therefore its interaction with water is unknown.	Many shape memory polymers have not been produced into a rope yet, therefore its interaction with water is unknown.
Ability to work with current lobster fishing equipment	Shape memory alloys have not been applied to an existing rope yet, therefore its ability to work with current lobster fishing equipment is unknown.	Many shape memory polymers have not been produced into a rope yet, therefore its ability to work with current lobster fishing equipment is unknown.
Ability to be spliced	Shape memory alloys have not been applied to an existing rope yet, therefore its ability to be spliced is unknown.	Many shape memory polymers have not been produced into a rope yet, therefore its ability to be spliced is unknown.

Abrasion Resistance	Shape memory alloys have not been applied to an existing rope yet, therefore its abrasion resistance is unknown.	Many shape memory polymers have not been produced into a rope yet, therefore its abrasion resistance is unknown.
Breaking Strength	An exact breaking strength of a shape memory alloy rope cannot be determined, however this material will have a negligible effect once applied to an existing lower breaking strength rope.	Many shape memory polymers have not been produced into a rope yet, therefore the breaking strength of a shape memory polymer rope is unknown.
Cost	The exact cost of SMAs varies based on the alloy used, however many shape memory alloys are still in development thus resulting in a high cost.	The cost of shape memory polymers varies based on the plastic used, however additional manufacturing processes will be needed to be developed in order to produce a SMP rope thus resulting in a high cost.
Diameter	Shape Memory Alloys are produced into wire strands ranging from 0.075mm to 1.25mm in diameter, therefore it can be applied to existing ropes with varying diameters.	Once shape memory polymers are extruded into fibers, they can be twisted into any size diameter rope.
Specific Gravity	Shape memory alloys will be applied to existing ropes which have specific gravities greater and less than one.	Many shape memory polymers have not been produced into a rope yet and have ranging physical properties, therefore the specific gravity is unknown.
UV resistance	Shape memory alloys have not been applied to an existing rope yet, therefore its effect on UV resistance is unknown.	The UV resistance of SMPs varies depending on the plastic, therefore the UV resistance of a SMP rope is unknown.
Additional Notes	Shape memory alloys have the ability to be programmed into a coil shape.	Shape memory polymers have the ability to be programmed into a coil shape.

Material	SMAs are commonly produced from alloys of Copper, aluminum, nickel, zinc, iron, manganese, or silicon (Lin, 2008).	"Essentially, all polymers are shape memory polymers" (B. Volk, personal communication, 10/3/13). This means that there is wide range of plastics that have a shape memory effect.
Manufacturing Process	Shape memory alloys are produced into wire strands which can be programmed and then twisted with existing synthetic fibers to produce a rope.	Shape memory polymers can be extruded into plastic fibers which can be programmed and then twisted into a rope.

Appendix G: Coatings Summary Table

Rope Characteristics	Maxijacket Urethane Coating	TrueKote CS-100	Truecoat CS-252
Production State	Maxijacket Urethane Coating is currently produced and sold by Yale Cordage. This coating is currently used with ropes in the climbing and tree removal industries (Yale Cordage, n.d.).	TrueKote CS-100 is currently produced and sold by Industrial Polymer Corporation. It is currently used to coat ropes for holding large vessels in port (Industrial Polymer Corporation, 2013).	Truecoat CS-252 is currently produced and sold by Industrial Polymer Corporation. It is used to coat ropes for holding large vessels in port (Industrial Polymer Corporation, 2013).
Ability to be used as a vertical line in the lobster industry	Maxijacket Urethane Coating has the ability to resist snagging on rocks and is waterproof. These characteristics allow a rope with Maxijacket coating to be used as a vertical line in the lobster industry (S. Yale, personal communication, 10/8/13).	TrueKote CS-100 is a waterproof coating which can be used with existing ropes however, there is no information on how this coating will perform as a vertical line in the lobster industry (Industrial Polymer Corporation, 2013).	Truecoat CS-252 is a waterproof coating which can be used with existing ropes, however there is no information on how this coating will perform as a vertical line in the lobster industry (Industrial Polymer Corporation, 2013).
Flexibility	Once Maxijacket coating is applied to an existing rope, the flexibility of that rope is not altered (Sherrill Tree, personal communication, 10/11/13).	Once CS-100 is applied to an existing rope, this coating still provides good flexibility, however the exact flexibility varies based on the diameter and thickness of the coating (Industrial Polymer Corporation, personal communication, 10/11/13).	Once Truecoat is applied to an existing rope, this coating still provides good flexibility, however the exact flexibility varies based on the diameter and thickness of the coating (Industrial Polymer Corporation, personal communication, 10/11/13).

Interaction with water	Maxijacket is a waterproof coating therefore it will resist any soaking or wetness (S. Yale, personal communication, 10/8/13).	TrueKote provides a fully waterproof seal around an existing rope therefore it will resist any soaking or wetness (Industrial Polymer Corporation, 2013).	CS-252 creates a fully waterproof seal around an existing rope therefore it will resist any soaking or wetness. This coating also has an extremely low reactivity with salt water meaning that it will not degrade from being submerged in the ocean (Industrial Polymer Corporation, 2013).
Ability to work with current equipment	The Maxijacket coating has not been tested in conjunction with the equipment used in the lobster fishing industry, therefore its ability to work with this equipment cannot be determined.	TrueKote CS-100 coating has not been tested in conjunction with the equipment used in the lobster fishing industry, therefore its ability to work with this equipment cannot be determined.	Truecoat CS-252 has not been tested in conjunction with the equipment used in the lobster fishing industry, therefore its ability to work with this equipment is unknown.
Ability to splice	Once applied to an existing rope, Maxijacket coating does not inhibit the ability to splice the rope (Yale Cordage, n.d.).	Once CS-100 is applied to an existing rope, the rope no longer has the ability to be spliced with another rope (Industrial Polymer Corporation, personal communication, 10/11/13).	Once CS-252 is applied to an existing rope, the rope no longer has the ability to be spliced (Industrial Polymer Corporation, personal communication, 10/11/13).
Abrasion Resistance	Maxijacket Urethane coating provides a low abrasive coating which increases its ability to be worked with (Sherrill Tree, personal communication, 10/11/13).	TrueKote CS-100 provides a low abrasive surface finish once applied to an existing rope (Industrial Polymer Corporation, personal communication, 10/11/13).	Truecoat CS-252 coating provides outstanding resistance to abrasion to an existing rope (Industrial Polymer Corporation, 2013).

Breaking Strength	Once applied to a lower breaking strength rope, Maxijacket coating does not change the overall breaking strength of the rope (Sherrill Tree, personal communication, 10/11/13).	Once TrueKote CS-100 is applied to an existing lower breaking strength rope, the breaking strength is not altered (Industrial Polymer Corporation, personal communication, 10/9/13).	Truecoat CS-252 does not alter the breaking strength once applied to an existing lower breaking rope (Industrial Polymer Corporation, personal communication, 10/9/13).
Cost	The cost of maxijacket is $92 per gallon of liquid coating. A gallon of this coating is enough to coat at least 1200 feet of 0.375 inch diameter rope (S. Yale, personal communication, 10/8/13).	One gallon of TrueKote CS-100 costs $61.65. In order to coat 1200 feet of rope, 9.2 gallons of CS-100 are required which creates an additional cost of $567.18 per 1200 feet of rope (Industrial Polymer Corporation, personal communication, 10/11/13).	One gallon of Truecoat CS-252 costs $50.47. In order to coat 1200 feet of rope which creates an additional cost of $557.18 per reel of rope (Industrial Polymer Corporation, personal communication, 10/11/13).
Diameter	Maxijacket is a thin coating once applied to a rope therefore providing a negligible change in diameter (S. Yale, personal communication, 10/8/13).	TrueKote CS-100 is a thick coating which increases the diameter of an existing rope by at least 0.125 inches (Industrial Polymer Corporation, personal communication, 10/11/13).	TrueKote CS-252 is a thick coating which increases the diameter of an existing rope by at least 0.1 inches to 0.25 inches depending on the cure time of the coating (Industrial Polymer Corporation, 2013).

Specific Gravity	Once Maxijacket Urethane coating is applied to an existing rope, the coating does not change the rope's ability to sink or float (Sherrill Tree, personal communication, 10/11/13).	TrueKote CS-100 has a specific gravity of 1.05 and will therefore alter an existing rope to have an additional tendency to sink (Industrial Polymer Corporation, 2013).	Truecoat CS-252 has a specific gravity of 0.88 which will has a tendency to be neutrally or slightly buoyant. However, upon speaking with the manufacturer, he concluded that this coating would not change whether an existing rope sinks or floats (Industrial Polymer Corporation, personal communication, 10/11/13).
UV resistance	When Maxijacket coating is applied to a rope, it provides additional UV resistance (Yale Cordage, n.d.).	TrueKote CS-100 is partially made of an aliphatic urethane which is well known in the rubber industry to have excellent outdoor performance in direct UV sunlight (Industrial Polymer Corporation, personal communication, 10/11/13).	Truecoat CS-252 is partially made of an aliphatic urethane which is well known in the rubber industry to have excellent outdoor performance in direct UV sunlight (Industrial Polymer Corporation, personal communication, 10/11/13).
Additional Notes	This coating is applied by dipping an existing rope into the liquid coating.	This coating is applied by dipping an existing rope in the liquid coating. This coating has a 45 minute working time and usually takes at least 24 hours to fully cure (Industrial Polymer Corporation, 2013).	This coating is applied by dipping an existing rope in the liquid coating. This coating has a very short working time and can take up to 15 days to fully cure (Industrial Polymer Corporation, personal communication, 10/11/13; Industrial Polymer Corporation, 2013).

Appendix H: Data sheet for TrueKote CS-100

Technical Data
TrueKote CS-100
January 1, 2003

Page 1 of 2

Description

TrueKote CS-100 is a protective hand applied coating for rope and closed cell flexible foam. It provides a slow 45-minute working life and may also be used as a casting product. TrueKote CS-100 protects rope rigging against damage from cuts and abrasion. Over flexible foam it provides a durable play surface, which resists cuts and punctures. TrueKote CS-100 is also used for encapsulating or potting fittings and eyes used in marine rope riggings.

Application

Service temperature range is –40° F to 200° F.

Typical Properties

	Viscosity	Specific Gravity	Weight Per Gallon
Component A	12500	1.03	8.59
Component B	200	1.13	9.39
Mixed	7500	1.05	8.72

Mixing Ratio	
By volume	100 parts A to 18.58 parts B
By weight	100 parts A to 20 parts B

Work life	45 minutes @ 72° F
Cure time	12 hours @ 72° F
Tack free	6 hours @ 72° F
Ultimate cure	7 days @ 72° F
Recoat	16 hours minimum, 96 hours maximum
Set time and Demold depend on temperature and relative humidity	

Physical Properties

	Test Method	Value
Hardness	ASTM 2240-85	85 Shore A
Tensile strength	ASTM D412	2850
Elongation	ASTM D412	450%
Tear strength	ASTM D412	385
Volatile organic compounds	ASTM D2369	0%
Fungus resistance		Non nutrient
Reparability		Excellent
Shrinkage (inch)		.0005 m/m
Water absorption		0.01

Color Clear

Storage
Shelf Life

TrueKote CS-100 is shipped from the factory in sealed containers. The containers should be stored in a cool dry area that is protected from direct sunlight and moisture. Storage temperatures should not exceed 80° F. The shelf life of factory sealed containers stored under these conditions is six months. Containers that have been opened should be resealed immediately after material has been removed in order to prevent solvent evaporation.

Packaging

TrueKote CS-100 is available in convenient 1-quart, 1-gallon and 5-gallon kits.
TrueKote CS-100 has a non-hazardous rating for shipping.

Appendix I: Truecoat CS-252 Data Sheet

TRUECOAT CS-252 Urethane elastomer
06/11

DESCRIPTION:

TRUECOAT CS-252 is a two component, high performance elastomer, for coating or casting into thick section. It cures to a high performance urethane elastomer that has high physical properties and outstanding resistance to abrasion. . TRUECOAT CS-252 may also be used as a coating for soft foam, floor coatings, flexible bumper, impact resistance pads for playgrounds, horse farms and polymer rope applications. TRUECOAT CS-252 may also be used as a protective coating for outstanding extended wear application on most metallic surfaces.

PROPERTIES:

LIQUID PROPERTIES OF COMPONENTS:

TRUECOAT CS-252 consists of a resin component, which provides the basic chemical backbone of the urethane, and a curative component, which promotes cross-linking of the resin, which results in the cured urethane elastomer. Typical liquid properties are shown in the table below.

Component	Resin Properties	Curative Component	Mixed Component
Color	Clear	Black	Black
Lbs. Per gallon	7.72	8.51	7.76
Weight solids, %	78.0%	97.0%	69.46%
Volume solids, %	63.20%	96.63%	65.18%
Viscosity, Brookfield ccps, @ 75 F	3,800	4	350
Flash point, TCC	102 F	102 F	102 F
VOC %	32%	3%	30.54%

PHYSICAL PROPERTIES OF CURED COATING:

Typical properties of TRUECOAT CS-252 cured at ambient temperatures are shown in the table below: Heat curing 130 F greatly reduces time to ultimate cure.

Tensile Strength (ASTM-D412 Die-C)	4325 psi
Tear strength (ASTM-D624, Die-C)	563 pli
Elongation (ASTM-D412 Die-C)	725 %
Hardness, Durometer A	75 A

ABRASION RESISTANCE:

TRUECOAT CS-252 has excellent abrasion resistance and will out wear many other materials when subjected to impingement or slurry abrasion.

HIGH OR LOW TEMPERATURE PROPERTIES:

TRUECOAT CS-252 has been successful at temperatures up to 180 F. Under wet or humid conditions at elevated temperatures, TRUECOAT CS-252 is superior to most other urethanes. Although TRUECOAT CS-252 becomes stiffer at lower temperatures, it still remains flexible at temperatures as low as –70 F.

CHEMICAL RESISTANCE:

TRUECOAT CS-252 has excellent chemical resistance in the pH range of 2 to 12. Resistance to most oils at room temperature is good, but resistance to solvents is generally poor. The table below gives an indication of resistance to some chemicals; however, users should conduct their own tests.

Chlorinated water. . . . . . . E Sea water. . . . . E Nitric acid,
5% . . . . P Toluene . . . . . . P Hydrocholoric acid, 5% .
. P MEK. . . . . P Phosphoric acid, 5% . . . G
Ammonia . . . . . F Kerosene . . . . . P

* G – Good, E – Excellent, F – Fair, P – Poor

COVERAGE:

The theoretical dry coverage of TRUECOAT CS-252 is 1045-mil square foot per mixed gallon of material. Overspray and waste must be taken into account when estimating the quantity of material required for a particular project.

CURE TIMES:

The time required for TRUECOAT CS-252 to cure is dependent upon temperature. A 75% cure is generally sufficient for mild abrasion and submersion. The cure times shown below are for a 100-mil thick coating; cure times should be increased by 50% for a 250-mil thick coating.

	50 F	75 F	130 F
75% cure	6 days	3 days	1 day
95% cure	15 days	7 days	3 days

CURE TIMES:

A 95% cure can be considered a complete cure for practical purposes, although all urethanes, including heat-cured urethanes, show improved physical properties after aging several weeks or months.

APPLICATION INSTRUCTIONS:

SURFACE PREPARATION:
TRUECOAT CS-252 should only be applied to surfaces that have been properly prepared. Most common materials such as steel, aluminum, fiberglass, rubber, urethane, brick, concrete, and wood can be coated with TRUECOAT CS-252. To obtain maximum adhesion most substrates must be gritblasted, abraded or etched before applying TRUECOAT CS-252. Metal surfaces should be gritblasted to SSPC-SP-10 "Near White Metal Blast" and should exhibit a 2 to 4 mil surface profile. Metallic substrates must always be dry True Coat CS-252 is applied.

Mix Ratios:

By weight: Component A (Clear)	100 parts	Component B (Black) 6.67 parts
By Volume	100 parts	6.52 parts

EQUIPMENT:

A single component airless spray machine with a minimum air: fluid pressure ratio of 20:1 will provide a good spray pattern with .015 to .026 inch orifice spray tip. When using larger spray tips or long hose lengths, it is advisable to use a machine with a 30:1 air: fluid pressure ratio. The spray machine should be equipped with Teflon packings, Teflon or nylon hose and a 100- mesh outlet filter. A tip filter may be required for small tips. The spray hose should be conductive and the spray machine should be grounded to an earth ground when spraying.

A Jiffy mixer or other propeller-type mixer used on air drill can be used to mix the urethane components.

STORAGE AND SHELF LIFE:

TRUECOAT CS-252 components are shipped from the factory in sealed containers that are purged with dry nitrogen. The containers should be kept tightly sealed and stored in a cool and dry area that is protected from direct sunlight and moisture. Storage temperature should not exceed 80 F. The shelf life of factory seal containers stored under these conditions is one year.

Containers that have been opened should be resealed immediately after material has been removed in order to prevent moisture contamination and solvent evaporation. Resin component containers should be purged with dry nitrogen if the contents are not used within 24 hours after opening.

MIXING COMPONENTS:

The resin portion of TRUECOAT CS-252 crystallizes when exposed to temperatures below 40 F and the curative portion may crystallize when exposed to temperatures below 20 F. This does not harm the components; however, the resin component should be warmed to 80– 100

and the curative component to room temperature and each component mixed well before using. The components should not be overheated and should be cooled to room temperature before mixing together. After long-term storage it is a good policy to stir each component before adding them together.

DO NOT mix resin and curative components until ready to use. The correct mixing ratio is three parts component A to one part component B by weight. TRUECOAT CS-252 will not cure properly if the correct component-mixing ratio is not used.

Mix the components together in a clean container using a power drill until a uniform blend is achieved. Scrape the sides and bottom of the container with a straight edge several times during the mixing operation to prevent unmixed material from sticking to the container. The total time required to mix the components should be about five minutes.

POT LIFE:

The pot life of TRUECOAT CS-252 is approximately 30 minutes at 75 F, 20 minutes at 100 F and 45 minutes at 50 F. After these times are exceeded for some additional time the material can still be sprayed using increased pressure or may be brushed or rolled on the substrate.

APPLICATION:

Standard techniques used in airless paint spraying work well with TRUECOAT CS-252. The proper spray tip should be selected for the job and the pressure of the pump should be adjusted to obtain an even spray pattern at the lowest pattern. The initial coat of TRUECOAT CS-252 should be a thin coat and should be applied from the bottom up so as to prevent overspray from depositing on the primed surface. On surfaces having a nap or rough texture, such as abraded rubber, optimum adhesive coats may be applied to a thickness of 5 – 20 wet mils, depending upon the position of the article being coated, the temperature and the elapsed time in the pot life. Each coat should be allowed to gel or dry to the touch, usually a period of 5 – 15 minutes, depending upon ambient temperatures, before the next coat is applied.

CLEAN UP:

Equipment must be cleaned immediately after use to prevent build up of cured urethane on internal parts of equipment. Solvents such as toluene or MEK works well for cleaning soiled spray equipment. As soon as urethane spraying is completed, solvent should be pumped through the pump, hose and spray gun until solvent comes out clear. The spray gun should then be removed from the hose and the end of the hose put in the solvent container near the pump suction and solvent should be circulated through the system for 15 – 20 minutes. The spray gun should then be attached to the hose and the system purged with fresh solvent.

Dispose of all empty TRUECOAT CS-252 component containers in accordance with local, state and federal regulations. Empty component containers can be rendered non-hazardous by.

CLEAN UP: continued

Rinsing the containers with a small amount of mixed material and allowing the solvents to evaporate. The containers will then contain non-hazardous cured urethane

REPAIR OF CURED COATING:

TRUECOAT CS-252 may be repaired by rough to a “suede” finish using a wire brush on and electric drill then clean the surface with M.E.K. (methyl ethyl ketone) then the application of more TRUECOAT CS-252.

SAFETY:

Vapors from TRUECOAT CS-252 contain isocyanates and solvents. Forced air ventilation must be used for all indoor applications. When working in tanks and other closed vessels or downstream from spray gun, fresh air breathing equipment should be worn. Chemical cartridge masks suitable for organic vapors may be used under some conditions with adequate ventilation. Protective clothing should be worn at all times. Both resin and curative
components contain flammable solvents and should be protected form sparks and open flames.

Avoid contact of components with skin and clothing as both resin and curative can cause skin and eye burns. In case of eye contact, immediately flush eyes with plenty of water for at least
15 minutes. If swallowed, DO NOT induce vomiting. Call a physician at once. Keep out of reach of children.

Appendix J: Existing Ropes Summary Table

Rope Characteristics	Novabraid Duraflex Lead Core	Novabraid Norpacific Gillnet Corkline High Tenacity
Production State	Duraflex lead core rope is currently produced for the gillnet fishing industry of the Northeast of North America (Novabraid, n.d. a).	Norpacific Gillnet Corkline is currently produced for the gillnet fishing industry on the North Pacific North American coast (Novabraid, n.d. b).
Ability to be used as a vertical line in the lobster industry	Currently, Duraflex rope is used on the ocean bottom, however it is unclear how this rope would perform in a rocky, rough ocean bottom (N. Prescott, personal communication, 10/7/13).	Norpacific Gillnet is currently used on the ocean bottom, however it is unclear how this rope would perform in a rocky, rough ocean bottom (N. Prescott, personal communication, 10/7/13).
Flexibility	Duraflex rope is a flexible rope and has the ability to twist and bend enough to coil (N. Prescott, personal communication, 10/7/13).	Gillnet Corkline is a flexible rope and can be twisted into a coil (N. Prescott, personal communication, 10/7/13).
Interaction with water	At this time, Duraflex rope's exact interaction with water is unknown, however it is currently used in an aquatic environment.	It currently unknown exactly how using Gillnet Corkline rope will interact with water, however, this rope is currently used in the oceanic environments.
Ability to work with current equipment	Althought Duraflex rope is currently used by Gillnet fisheries, it is unknown how this rope will perform with lobster fishing equipment.	Although Norpacific Gillnet Corkline is currently used by Gillnet fisheries, it is unknown how this rope will perform with lobster fishing equipment.
Ability to splice	Due to the lead core of Duraflex rope, this rope does not have the ability to be spliced (N. Prescott, personal communication, 10/7/13).	Norpacific corkline rope's ability to splice is currently unknown.

Abrasion Resistance	This rope has a polyester and polypropylene braided sleeve which provides an abrasion resistant surface (Novabraid, n.d. a).	This rope has a polyester and polypropylene braided sleeve which provides a low abrasive surface (N. Prescott, personal communication, 10/7/13).
Breaking Strength	The breaking strength of Duraflex rope is dependent on its varying diameters. This breaking strength ranges from 800 pounds to 2600 pounds. However, for a 3/8 inch diameter rope the breaking strength is 2000 pounds (Novabraid, n.d. a).	The breaking strength of Norpacific Gillnet rope varies from 1465 pounds to 2860 pounds depending on the diameter of the rope. However, for a 3/8 inch diameter rope, the breaking strength is 1465 pounds (Novabraid, n.d. b).
Cost	The exact cost of Duraflex is unknown, however a representative of Novabraid said that this rope does have a high cost due to the weight of the rope (N. Prescott, personal communication, 10/7/13).	The exact cost of Norpacific Gillnet Corkline is unknown at this time.
Diameter	Duraflex rope is currently produced in a variety of diameters ranging from 3/16 inch to 9/16 inch (Novabraid, n.d. a).	Gillnet Corkline rope is produced in diameters ranging from 3/8 inch to 1 inch (Novabraid, n.d. b).
Specific Gravity	The specific gravity of the total Duraflex rope has not yet been determined, however the specific gravity of the primary lead component of the rope is 11,340 meaning that it will rapidly sink in water.	The specific gravity of Norpacific Gillnet rope is 1.27 meaning that it will sink when placed in water (Novabraid, n.d. b).
UV resistance	The braided sleeve on the outside of Duraflex lead core rope provides good UV resistance (N. Prescott, personal communication, 10/7/13).	Norpacific Gillnet Corkline rope has a braided sleeve which has been rated to be UV stable (Novabraid, n.d. b).

Appendix K: Multi-Variable Assessment Tool

Considerations	**Weighting**			Current Rope (Polysteel)
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	3
Ability to be used in muddy bottoms	2	1	3	3
Ability to be used in rocky bottoms	2	1	3	3
Ability to coil	2	0	2	3
Ability to handle when wet	1	0	1	X
Ability to resist wear in hauler	2	0	2	2
Ability to splice the rope	1	1	2	3
Abrasiveness	2	2	4	2
1,500 pound Breaking Strength	2	2	4	1
Cost compared to current ropes	2	0	2	2
Degradation of breaking strength	2	1	3	1
Diameter	2	2	4	2
Specific Gravity	2	0	2	2
UV resistance	1	0	1	2
Total				73

Considerations	Weighting			Shape Memory Alloy
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	1
Ability to be used in muddy bottoms	2	1	3	X
Ability to be used in rocky bottoms	2	1	3	X
Ability to coil	2	0	2	3
Ability to handle when wet	1	0	1	X
Ability to resist wear in hauler	2	0	2	X
Ability to splice the rope	1	1	1	X
Abrasiveness	2	2	4	X
1,500 pound Breaking Strength	2	2	4	2
Cost compared to current ropes	2	0	2	1
Degradation of breaking strength	2	1	3	X
Diameter	2	2	4	2
Specific Gravity	2	0	2	2
UV resistance	1	0	1	X
Total				30

Considerations	Weighting			Shape Memory Polymer
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	2
Ability to be used in muddy bottoms	2	1	3	x
Ability to be used in rocky bottoms	2	1	3	x
Ability to coil	2	0	2	3
Ability to handle when wet	1	0	1	x
Ability to resist wear in hauler	2	0	2	x
Ability to splice the rope	1	1	2	x
Abrasiveness	2	2	4	x
1,500 pound Breaking Strength	2	2	4	2
Cost compared to current ropes	2	0	2	1
Degradation of breaking strength	2	1	3	x
Diameter	2	2	4	2
Specific Gravity	2	0	2	x
UV resistance	1	0	1	x
Total				28

Considerations	**Weighting**			Maxijacket Urethane Coating
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	3
Ability to be used in muddy bottoms	2	1	3	3
Ability to be used in rocky bottoms	2	1	3	3
Ability to coil	2	0	2	2
Ability to handle when wet	1	0	1	X
Ability to resist wear in hauler	2	0	2	x
Ability to splice the rope	1	1	2	2
Abrasiveness	2	2	4	3
1,500 pound Breaking Strength	2	2	4	2
Cost compared to current ropes	2	0	2	2
Degradation of breaking strength	2	1	3	x
Diameter	2	2	4	2
Specific Gravity	2	0	2	2
UV resistance	1	0	1	3
Total				71

Considerations	Weighting			TrueKote CS-100
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	3
Ability to be used in muddy bottoms	2	1	3	x
Ability to be used in rocky bottoms	2	1	3	x
Ability to coil	2	0	2	x
Ability to handle when wet	1	0	1	x
Ability to resist wear in hauler	2	0	2	x
Ability to splice the rope	1	1	2	1
Abrasiveness	2	2	4	3
1,500 pound Breaking Strength	2	2	4	2
Cost compared to current ropes	2	0	2	1
Degradation of breaking strength	2	1	3	x
Diameter	2	2	4	2
Specific Gravity	2	0	2	2
UV resistance	1	0	1	x
Total				42

Considerations	**Weighting**			Truecoat CS-252
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	2
Ability to be used in muddy bottoms	2	1	3	x
Ability to be used in rocky bottoms	2	1	3	x
Ability to coil	2	0	2	x
Ability to handle when wet	1	0	1	x
Ability to resist wear in hauler	2	0	2	x
Ability to splice the rope	1	1	2	1
Abrasiveness	2	2	4	3
1,500 pound Breaking Strength	2	2	4	2
Cost compared to current ropes	2	0	2	1
Degradation of breaking strength	2	1	3	x
Diameter	2	2	4	2
Specific Gravity	2	0	2	2
UV resistance	1	0	1	x
Total				40

Considerations	Weighting			Novabraid Duraflex Lead Core
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	3
Ability to be used in muddy bottoms	2	1	3	x
Ability to be used in rocky bottoms	2	1	3	x
Ability to coil	2	0	2	x
Ability to handle when wet	1	0	1	2
Ability to resist wear in hauler	2	0	2	x
Ability to splice the rope	1	1	2	1
Abrasiveness	2	2	4	3
1,500 pound Breaking Strength	2	2	4	2
Cost compared to current ropes	2	0	2	x
Degradation of breaking strength	2	1	3	x
Diameter	2	2	4	2
Specific Gravity	2	0	2	2
UV resistance	1	0	1	2
Total				44

Considerations	Weighting			Novabraid Norpacifc Gillnet Corkline High Tenacity
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	3
Ability to be used in muddy bottoms	2	1	3	x
Ability to be used in rocky bottoms	2	1	3	x
Ability to coil	2	0	2	x
Ability to handle when wet	1	0	1	2
Ability to resist wear in hauler	2	0	2	x
Ability to splice the rope	1	1	2	x
Abrasiveness	2	2	4	3
1,500 pound Breaking Strength	2	2	4	2
Cost compared to current ropes	2	0	2	x
Degradation of breaking strength	2	1	3	x
Diameter	2	2	4	2
Specific Gravity	2	0	2	2
UV resistance	1	0	1	2
Total				42

Appendix L: Multi-Variable Assessment Tool Guide

The following is an explanation of how to use Multi-Attribute Utility Theory (MAUT) with respect to the North Atlantic right whale entanglement problem. MAUT is a multiple-criteria decision-making tool that is specifically useful in risk analysis when a high level of uncertainty is involved (Tzeng and Huang, 2011, p.194). Since it is difficult to assess the effectiveness of alternatives meant to reduce North Atlantic right whale entanglement, MAUT assists us in accommodating for this high level of uncertainty. This memo will go through step by step on how to set up a MAUT table and how to do the calculations.

In MAUT, options called **alternatives** are assessed on a variety of criteria called **considerations**. Considerations can include factors such as cost and safety. These considerations are assigned a **weight** which indicates their importance to the situation being investigated. Alternatives are assigned **scores** based on how well they meet these given considerations. Scores are multiplied by the weight of that consideration and then these products are summed for each alternative. This sum is representative of how well alternatives solve the problem. MAUT is useful in this project given that we need to take into account a variety of different perspectives including the safety of the whales, perspectives within the lobster fishing industry, and available technology when analyzing alternatives.

<u>a. Considerations:</u>

All characteristics that are deemed important are defined in the methodology of MAUT as **considerations**. First, the relative importance of each consideration needs to be assessed. Each consideration can be given two relative importance ratings, one for the importance to the lobster fishing industry and a second for the health of the North Atlantic right whales. The importance rating is based off of how much impact the consideration would have on the lobster fishing industry or the North Atlantic right whales. The rating system for the relative importance is as follows:

Rating	Relative Importance
2	High
1	Moderate
0	None

The two relative importance ratings are then summed to give the overall importance score. Therefore, a scale for overall importance of 0-4 is implemented with 0 being *of no importance to either group* and 4 being *of great importance to both groups.* The weighing process is a critical step because some considerations are more influential than others and this influence needs to be reflected in the assessment of alternatives. The considerations are then listed in alphabetical order on the left side of the worksheet with their respective weights for each perspective on the right.

b. Scoring the Alternative

Each **alternative** is listed in a separate column in the worksheet and then given a rating on each consideration using a scale of 1 to 3. A “3” is defined as *exceeds the consideration* while a “1” is defined as *does not meet the consideration*. A rating of “2” is neutral, defining the alternative as satisfying that consideration. The rating system we used is depicted below.

Score	Significance of Rating
3	Exceeds
2	Meets
1	Does Not Meet

c. Calculating the Decision

The decision is defined in the MAUT methodology as giving each alternative a **score**. The score is calculated by multiplying the weight for each consideration (0 to 4) by the compatibility rating for each consideration (1 to 3). These products are then summed to find the **total assessment score** for each alternative. Alternatives with higher scores are defined as better **decisions**. However if some alternatives cannot be given a rating for some considerations a total assessment score for alternatives can only be calculated in part. This can be taken into account by performing an additional step of assigning an uncertainty score. If an alternative could be scored on greater than 11 considerations, it had a low uncertainty rating. If an alternative could be scored on 6-10 considerations, it had a moderate uncertainty rating. If an alternative could only be scored on 1-5 considerations, it had a high uncertainty rating. These uncertainty ratings allow us to better understand the limitations of the score.

The following is an example of a MAUT worksheet:

Considerations	**Weighting**			Alternative
	Lobstermen	Right Whales	**Total**	
Ability to be readily produced for the lobster fishing industry	1	1	2	
Ability to be used in muddy bottoms	2	1	3	
Ability to be used in rocky bottoms	2	1	3	
Ability to coil	2	0	2	
Ability to handle when wet	1	0	1	
Ability to resist wear in hauler	2	0	2	
Ability to splice the rope	1	1	2	
Abrasiveness	2	2	4	
1,500 pound Breaking Strength	2	2	4	
Cost compared to current ropes	2	0	2	
Degradation of breaking strength	2	1	3	
Diameter	2	2	4	
Specific Gravity	2	0	2	
UV resistance	1	0	1	
Total				

Appendix M: Educational Program Recommendations

The following are recommendations for an educational program about the entanglement issues of North Atlantic right whales derived from the interviews conducted with Maine lobstermen. The lobstermen interviewed fished along the coast of Maine with about half of them offshore and half of them inshore. These interviews were conducted in person as well as by phone. Through our interviews with lobstermen, we concluded that some lobstermen do not acknowledge the overlap of that the North Atlantic right whales and their gear. One interviewee stated that he has seen “three whales in the last 30 years”. An educational program could help educate lobstermen about North Atlantic right whales and the overlap with the lobster fishing industry.

Purpose: Inform the lobster fishing industry of the North Atlantic right whale entanglement problem to promote collaboration with the New England Aquarium to develop and implement a solution.

Intended Audience: Lobstermen along the Atlantic Coast of the United States of America

Form: Educational program consisting of a combination of brochures, YouTube videos, social media campaigns, and presentations.

Recommended Content:

- **Biological information about the North Atlantic right whales.** Lobstermen have showed particular interest in the species in itself and are curious about it. Specific details that must be addressed include basic information such as how big they are, what they eat among others.
- **Location and migration path of the North Atlantic right whales.** Lobstermen do not acknowledge that many of the lobster traps laid down are in the same areas where the North Atlantic right whales reside therefore there is a real risk for entanglements in lobster gear.
- **How whales can get entangled with the vertical line.** To understand the problem lobstermen must understand how whales can get entangled in lobster traps. Most of them do not acknowledge the risk that their gear could end up being entangled in right whales. Not much information is available at the moment but further innovations of the right whale entanglement simulator will make the visual representation possible.
- **The low population and the delicate state of the North Atlantic right whale as an endangered species.** The North Atlantic right whale is in real danger but is on the verge of being able to rebound back if the number of whales killed by humans is decreased. Lobstermen need to see that the species population is so endangered.
- **Basic Information on how to avoid North Atlantic right whale entanglement.** Lobstermen should be shown the current ideas proposed to reduce the severity

of right whale entanglements. The idea that strategies can be beneficial both for the lobstermen (by reducing their long-term expenses) and for the North Atlantic right whales should be stressed. If lobstermen can realize that the strategies are being developed to help them as well the strategies can be implemented more successfully.

- **Invitation to get in contact with the New England Aquarium.** Lobstermen want to get their views of the problem taken into account and the only real solution will come from collaboration between the New England Aquarium and the lobstermen.

We recommend that further research be done to design an educational program that is informative, motivating and based in psychological sciences about how to influence people like lobstermen, in contexts like this, to change their behavior.

Appendix N: Group Summative Assessment

At the beginning of this term, we quickly realized that working on one task together as a group was not an efficient use of our time. While writing different components of the report, most assignments took much longer than expected. In order to make the most effective use of our time, we decided that we should split up different tasks amongst group members. In this approach, we felt that we would be able to pursue more aspects of the project quicker and in a more complete manner than before. When dividing tasks, we aimed to have each group member work in areas they felt the strongest. For example, Emily and Sarah felt more comfortable with summative writing while Tyler and Francisco were more confident with technical writing, so we aimed to divide the chapters in our report accordingly. In our past experiences, our writing styles have clashed thus making editing more difficult. By splitting up these chapters based on writing styles, we would ideally avoid potential conflicts amongst group members.

After discussing this method of dividing our workload amongst group members, we made it the main focus in our first formative assessment. In doing this, we were able to receive advisor feedback regarding this method before implementing it for ourselves. In our assessments, we were also able to address other issues within the group and created attainable individual goals. For example, our group noticed that we could become easily sidetracked and distracted while working on the project. To address this issue, individuals set goals limiting themselves to how often they could indulge in distractions like social media. A major factor in the success in addressing some of these issues was that all group members were able to be completely honest during our formative assessments. Honesty helped to create a clearer picture of our group dynamics. Another factor that ensured the resolution of some of our issues was that group members were encouraging and supportive towards other's goals.

Our group strived to resolve any conflicts before bringing it to the attention of our advisors. We were able to do this with both with our writing strategy and when conflicts arose regarding our trip to Maine. When planning our trip to Maine, there was a conflict of interest amongst group members regarding whether to go on the Maine trip. As a group, we were able to dedicate a period of time to resolving this conflict by fully understanding everyone's interests as well as weighing all interests to validate our solution. In the end, we all had a great time on our trip and accomplished a great deal of work by splitting up tasks between group members.

Although our group resolved many of the conflicts that arose throughout the course of this project, there were still some issues we struggled to rectify. These unsolved problems were mainly in the areas of writing and group expectations. For example, although we aimed to divide the project based on strengths, this execution did not happen the way we had agreed upon and led to an unequal division of work. For example, some group members ended up writing and editing more than others. In the future, we feel that by creating more clearly defined expectations and deadlines, this problem could be resolved.